Analysis of Construction Projects using a System Dynamics Methodology.

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ABSTRACT

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To manage a design and construction project, conventional tools, like bar-charts and schedules with critical paths, are applied at the operational level to control time of each activity. In developing a schedule, the manager makes assumptions about a duration in relation with a level of manpower and a productivity. Because the reality is more complex, these tools do not allow a global view of the interactions between the numerous variables involved in this dynamic process. With these tools, it is not possible to analyse the net effect of a policy, like a fixed schedule, a ceiling on manpower, a change of the productivity or an addition of modifications on the project control baselines over time.

This system dynamics model can generate the effect of these management policies in relating the evolution of specific variables over time into three interrelated subsystems: the design, the construction and the procurement.

TABLE OF CONTENTS

ILLUSTRATIONS

LIST OF TABLES

LIST OF APPENDIXES

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DEDICATION

This thesis is dedicated to my wife, Martine Gaudet, who not only provided wifely patience in waiting time with our daughter Andreanne during many evenings when I worked on the computer located at my business office, but she encouraged me during the past two years and she also made many substantial contributions in revising the earlier versions of the manuscript to enhance the finished work.

CHAPTER I

INTRODUCTION

In the construction industry, the management implies to be able to analyse the impact of decisions, principally for major construction projects due to the larger number of external and internal factors.

The scope of this study is to present, first of all, a model that describes the interactions or cause-and-effect links between the variables of three major sub-systems: the design, the construction and the procurement. The design and the construction subsystems include, each of them, interrelations between variables like the workforce, the schedule, the cumulative progress and the cost; the procurement subsystem controls variables like orders of material, material delivered on site. Also, in each sub-system, specialties are interrelated to better represent the progress of one specialty in regard to the other.

The objectives of this study is to desmontrate that the system dynamics technique is a useful tool to analyse the evolution of a variable behavior over time, to help clarify the thought about the interrelations between variables like the productivity, the quality, to analyse the impact on variables if the intensity of one or more variables is modified like the quality of resources available, the fixed-schedule policy, the fast-track policy, the increase of changes during the construction, a modified inflation rate, and to confirm the choice of an acceptable policy.

Chapter II presents a description of the complexity of the construction process: the interrelations between the design, the procurement and the construction phases, the description of the internal and external constraints that could have desastrous consequences on a project life, the operational method normally used to plan and monitor a project and finally the advantages of using a fast-track project.

Chapter III explains the system dynamics concept which is the theory of feedbacks: to be able to run a model, first of all, a diagram of causes and effects is drawn, then the interrelations diagram is converted in a flow diagram to show the role of each variable and to help the modeler define the model equations; various mainframe computer and micro-computer simulations are realized in modifying the values of specific variables to see the effect over time on variables like time, cost and workforce. Before introducing the model presentation, similar technic used in relevant literature are described in chapter IV; two models are described: the simplified model of Dr. Richardson and the model of Dr. Tarek. Both of these models are related to research and development.

Chapter V defines the variables of the three subsystems in order to explain about 350 equations; the causal diagram of the design subsystem and the construction subsystem are similar because the same parameters are implied, but the weight given to one variable that affects other variables is not necessarily the same. The procurement subsytem is related to the design progress and in return affects the construction progress. Cost equations estimate the total project cost in constant and current dollars to analyse the net economic effect of a policy.

A system dynamics model helps to clarify our processes of thought and to validate some policies already adopted by the construction managers. Chapter VI presents graphical and tabular outputs of simulations to show the behavior modes of variables with various strategies.

If learning is possible from these simulations to understand where the emphasis should be placed, where the effort should be applied, the management capabilities will be increased to achieve project control on cost, time and quality.

CHAPTER II

PROCESSES IN THE CONSTRUCTION INDUSTRY

2.1 Life Cycle Project and Constraints

In the construction industry, sequential steps are involved: initial concept, preliminary design, detailed design and engineering, procurement, construction and commissioning (see figure 1).

CONCEPT → DESIGN → CONSTRUCTION / PROCUREMENT → COMMISSIONING

|← TIME →|

figure 1. Life cycle of a construction

Any company proceeding to implement a capital project operates under two basic groups of constraints:

1. one internal, which is largely the result of company policy or lack of policy such as:

   1.1 labor-management relations

   1.2 organizational characteristics

   1.3 scheduling and coordination; (un)proper control and coordination over the sequencing and interfacing of work

1.4 key personnel; the changeover in key personnel disrupts the continuity of communications and the familiarity of the project managers with job related matters

1.5 skill in craftsmen; lack of skill in craftsmen and the quality of training deteriorate quality of workmanship and productivity.

2. the external constraints summarized as social, inflationary, geographical, political which motivate some of the internal constraints and also constraint of the contractors, subcontractors, manufacturers, suppliers who contribute either directly or indirectly to the progress of the project.

While a project is under study during the early stages of design and order placement, the internal constraints are all important to the progress of the project. Once, however, the project is largely committed, the external constraints assume a dominating role. The relative impact and importance of these several external constraints will vary from country to country. All these determine the decision to build and the speed with which the project is brought to completion.

In the conventional case all design-construction inter-dependencies are eliminated using the general contractor as an interface. In this approach, when the design phase is complete, a set of tender documents is prepared by the consultants. After having awarded the contract, the construction can begin.

2.2 The Operational Method to Control Time

The activities in the construction phase are primarily sequential. In these sequential relationships, an assembly line approach can be adopted.

The design process consists of both sequential and reciprocal relationships. Reciprocal relationships are more difficult to control. Control mechanisms include mutual adjustment and feedback. Mutual adjustments is the process by which the people involved in the relationship work together to coordinate their effort.

The fast-track case is, however, not as clear cut. A reciprocal relationship still exists between designers, but it is now interlaced with the sequential construction activities. Instead of one sequential relationship between the design phase and the construction phase, there are now many such relationships. Coordination mechanism for the design is still mutual adjustment and feedback between designers (see figure 2). Construction is still controlled by scheduling and planning. In the fast-track case, however, the interface between design and construction takes on a critical nature.

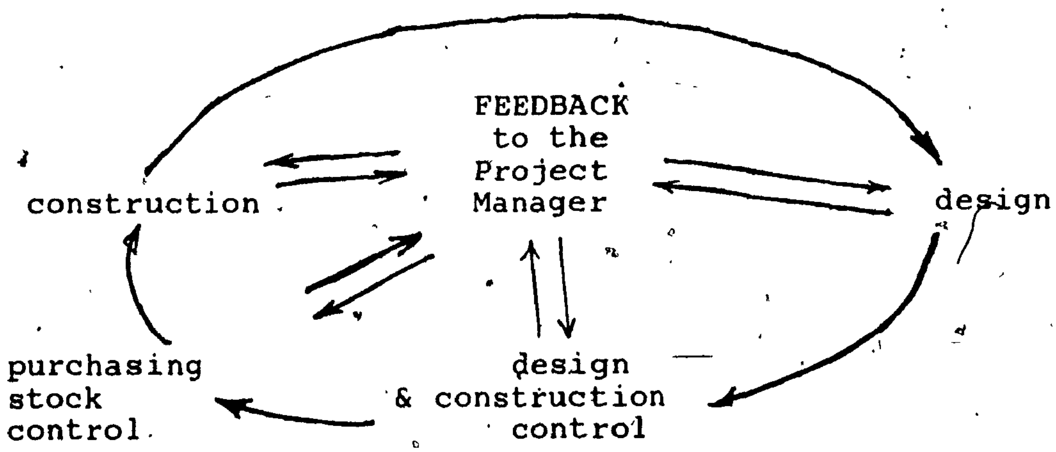


figure 2. Feedback cycle

The oldest planning technique of interest involves the use of bar charts, sometimes called Gantt charts due to the originator, Henry Gantt. Network analysis replaces the familiar Gantt chart to improve control of project and to show the interdependence of each activity or task with all the others in the project. Network analysis encourages a logical progression of planning; the best network analysis known are certainly the CPM (Critical Path Method) and PERT (Programme Evaluation and Review Technique). The heart of any network analysis technique is the arrow diagram. The succeeding activity cannot begin until all activities preceding have been accomplished.

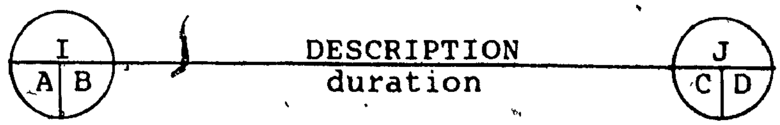


figure 3. Representation in a C.P.M. schedule

2.3 Changes during the construction

The basic structure of the construction industry makes change orders inevitable. Construction projects generally involve contracts between the owners and one or more construction contractors that have different types of resources interacting with each other under a very decentralized system of control. The most common problem experienced by contractors after the contract is signed, is to recognize and prove the impact a change or "extra" work may have on many downstream activities and the remaining time for performance.

Change is always expensive. The later changes occur, the more expensive they become. Change orders could not be examined in isolation, but had to be understood in relation to the system which produces them. In contract administration, change orders should be seen as a symptom, not a cause.

A diagrammatic representation of the work flow through the life of a project should also illustrate the cost of change, the effect of scope change on the work flow and the role of cost control in the accumulation of data. The interpretation of data is demonstrated as a continuing function for the control of cost, quality and time (see figure 3).

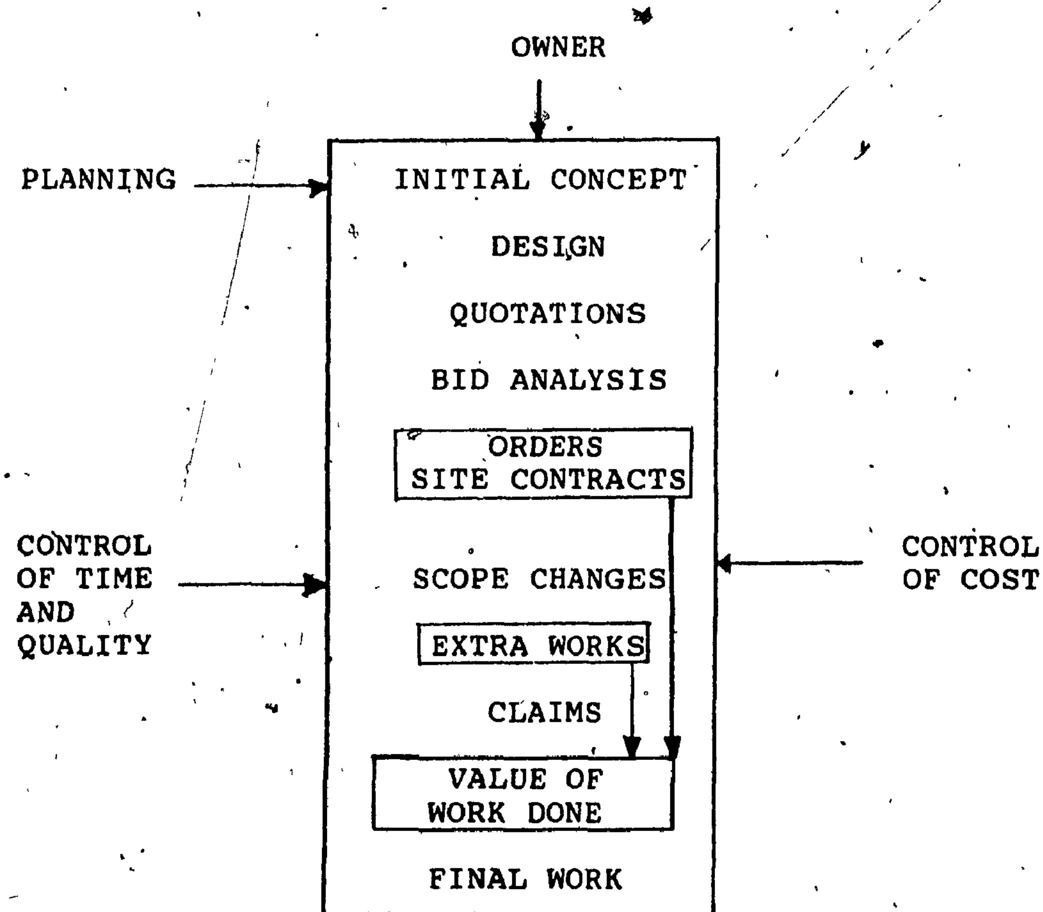


figure 4. The project cycle

Changes can still occur for a variety of reasons:

1. Poor definition of the project; as construction becomes

more complex, it is increasingly difficult for designers to understand field construction and to communicate their intentions to constructors

2. Mistakes or omissions in detailed design or contract (uncoordinated, suboptimized components: the materials which comprise a building are manufactured by many separate industries and companies); as a result, truly optimal combinations of components could be impossible to design and conflicts could arise
3. Unforeseen or differing site conditions or work conditions can have devastating results, giving rise to as many changes and delays
4. Site access
5. Owner actions that change the way in which the contractor executes the work and therefore change the contractor's cost of doing the work, although they may not change the end product
6. Contractor action for contractor convenience
7. Congestion of work areas and interferences between trades.

A problem arises not only when the contractor is faced with a major change but also with an inordinate amount of minor changes. It is conceivable that given a poorly coordinated design, these minor changes can be numerous for each period. While individually the amount of work is hardly worth processing, the accumulation of minor delays caused by the changes can have a detrimental effect on the overall project. Also, the actual effect of the minor change is not always recognized either by the contractor or the owner. Occasionally the magnitude of these minor changes will cause a contractor to lose control of a project.

These preceding changes could lead to all these changes, restaints, job conditions and damages could have various consequences on the work. The most known are:

1. Disruption;

   The characteristics of tasks may make them susceptible to disruption such as complexity, amount of interactions with other tasks, repetitiveness, and size of crew.

2. Rework;

   Rework in particular is extremely demoralizing. Lastly, if a change substantially changes the method of accomplishing an ongoing, repetitive segment of the project, learning curve improvements are lost. A change of resource allocation for a particular task can be brought about by a design change for that task or as a result of a change to a prior task.

3. Acceleration;

If the owner intends to lease the project being built, the owner will suffer damages in the form of rent lost due to construction delays. In some cases, the owner may suffer an especially damaging form of this type of loss where the opening of his facility is delayed until after the peak season for vacations, production, or sales.

More workers are added in order to finish the work earlier than the contract completion date. The contractor may accelerate in order to make up for his own delays or on request by the owner to complete a portion or all of the work before the agreed upon contract completion date. There may be increased standby time (idled equipment and labor demobilization and remobilization) and problems with congestion of the work area. "It is generally acknowledged that there is an optimum crew size which should not be exceeded if multiple shifts are employed; there are shift transition losses and probably some loss of accountability for performance. All of these actions can also decrease worker motivation...

The effect on labor productivity will vary depending on exactly what steps the contractor takes in accelerating the work. If the existing work force is put on overtime, productivity will suffer as a result of fatigue and other factors" [18].

4. Interruption;

"The owner may stop all or part of the work for various reasons... The effects of a work interruption on productivity include standby time if other work can not be found for the affected people, manpower expended for demobilization and remobilization, loss of learning curve imporvements, and damage to workforce morale...

Whenever work is stopped for a significant length of time and especially if the same people do not return to the job, some or all of the gains in productivity which have been realized through experience and practice will be lost" [18].

5. Change of sequence;

An owner may at any time ask the contractor to change a sequence which modifies the resources allocation in order to bypass a problem area, for instance, when the design is not completed, or to expedite the completion of an area to allow the owner to use the area as soon as possible.

Even if the crews in place continue with the same type of work, some loss of production associated with movement of equipment and material could be generated. "It could also cause conflicts between crews by changing the planned flow of crews through the site. If the affected crews are not able to continue with the same type of work, the effect would be similar to that of a work interruption" [18].

6. Change of resource allocation;

A change in resource allocation means that the expected resources to accomplish the task are not available because the contractor did not have enough time to implement a revised plan, requested by the owner. The productivity could be affected in reducing efficiency and damages workforce morale because there may be altered work methods, work area congestion and other disruptive effects on the contractor's work. It may involve any of the phenomena discussed previously (acceleration, interruption, change of sequence)

7. Impact on unchanged work;

The impact on the unchanged work takes into account the ripple effect on their own operation or that of follow-on subcontractors.

The increases in cost associated with these actions are often referred to as impact costs. Impact costs can be divided into three categories:

1. "indirect or overhead cost" [14] associated with an increase in overall project duration; the share of home office overhead cost
2. "escalation costs" [14]: material cost and wage rate escalation due to period of delay
3. "efficiency losses" [14]: production rate modified caused by disruption of the work. "A difficult area to deal with, yet of equal importance, is the potential for losses of efficiency in completing the unchanged work. The problem is effectively assessing the costs and convincing the owner that you are entitled to the added equitable adjustment" [14].

2.4 Necessity to Use Fast-track

With the traditional conventional construction method in one unique package following the rigid procedure of the design, procurement, construction phases, the duration of the total project would be too long. Fast-track construction can be, and is, employed for a wide variety of reasons. It may be used when site conditions are unknown or variable, because design cannot be finalized before construction begins, or when speed is the primary objective.

If a capital venture is to be successful with the expected return on the owner's investment, the project must be completed in time to meet the market. Telescoping a project, once defined, into as short a period as possible by having a sensible overlap between the various phases set out above, may well be essential if the whole process from project inception to project completion is not to become so long as to make the investment totally uncompetitive.

Is it more economic to fast-track large projects and save time on the normal schedule of a conventional project realized in rigid and independant phases? Fast-tracking should reduce the cost by around 30% compared to a conventional undertaking into account of escalation on material and the cost of borrowed money (see figure 5).

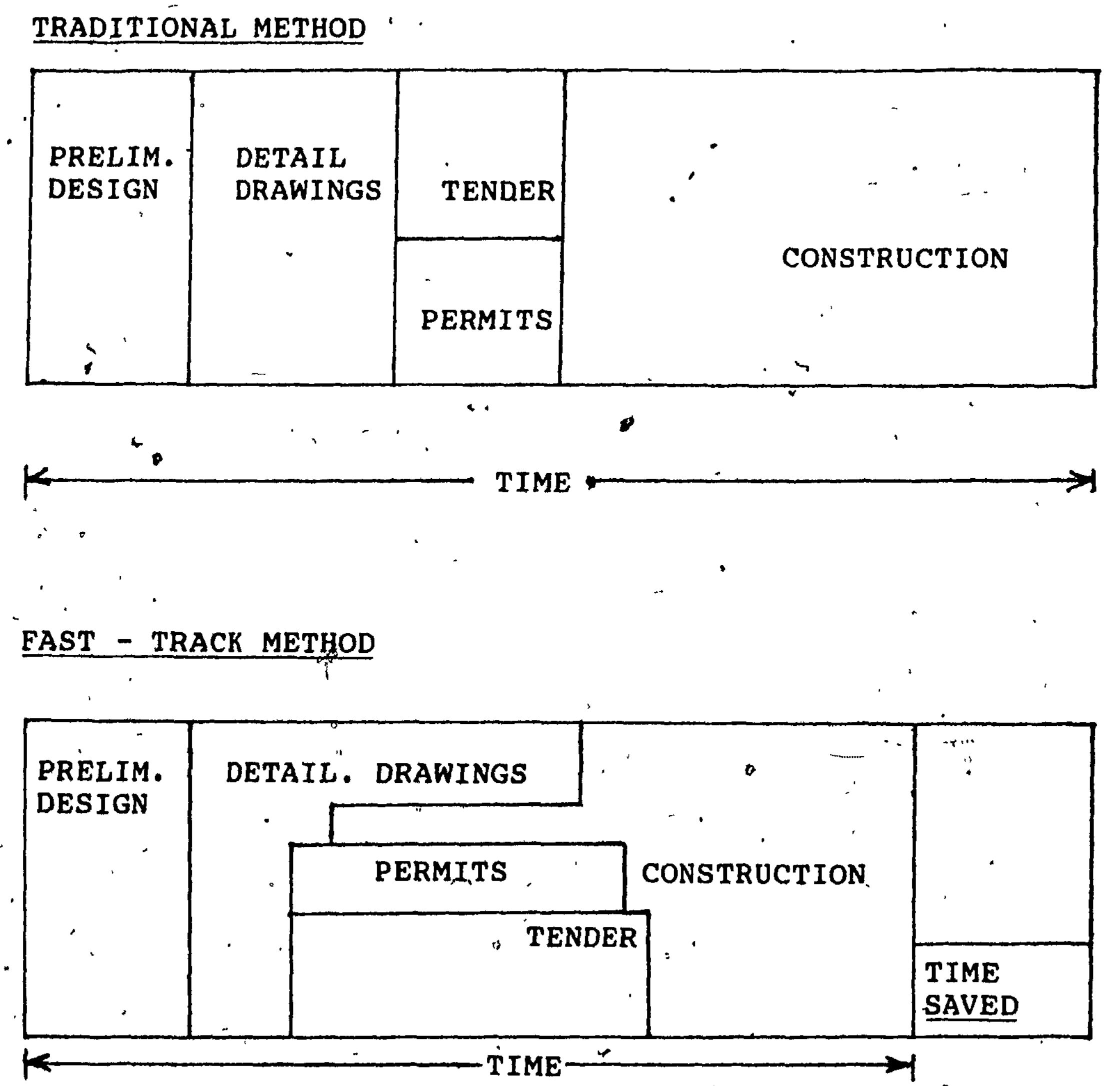


figure 5. Comparison of the traditional and fast-track methods

In a fast-track project, the construction is done at the same time that the design is done. A fast-track project is not clear cut but it is realized in design/built packages configurated to suit the needs of the construction.

In the fast-track case, construction activity precedence and durations are the same in the conventional case, the difference lying in the interlacing of the design process. Subcontractors and suppliers cannot be awarded contracts until the related designer has finished a work package. The subcontractors still depend on designers for shop drawings approvals. Shop drawings approval is considered a sequential construction activity in this study. It must be scheduled in both conventional and fast-track construction cases. In this case, one designer can impact the entire job once the float associated with their work package is exceeded. Construction is already underway and equipment and/or workers may be forced to remain idle while design problems are resolved.

A reciprocal relationship still exists between designers, but it is now interlaced with the sequential construction activities. Instead of one sequential relationship between the design and the construction phase, there are now many such relationships. Coordination becomes a major concern on fast-track projects, since the design and construction teams perform closely related activities which must be carefully managed.

In a fast-track, the project is subdivided in many work packages that are going to become more and more precise as the definition of the scope develops through configuration management. The construction of the first packages is planned as soon as possible and the manager tries to maintain continuity and avoid disruption in the continuous design/built process. In this process, the designer and the contractor are working more closely and often the designer is part of the contractor organization, this is called a design/built company.

Long lead time items such as steel, glass, masonry, precast, doors, hardware and electrical components can be set into motion before the overall design is complete.

A fast-track project generates rip-out and rework, not only on the design table but also on the field. Rip-out and rework are equivalent to negative productivity and affect the morale of workers and the dynamics of program performance. Major buildings are highly sensitive to quality control and schedule pressure. Extended delivery time, reduction of material availability, and schedule pressure result in work out of sequence, jeopardizing the cash flow and consequently the internal rate of return of the project.

In a major fast-track project, it is almost impossible with traditional operational methodological approaches to establish claims on "delay and disruption" costs and "ripple effects" of dealing with direct changes on original scope. On account of reciprocal relationships in a fast-track project, there is a need for a tool to properly assess the impact of scope changes on the project control baselines, such as duration, budget, quality and productivity.

CHAPTER III

THE SYSTEM DYNAMICS CONCEPT

System dynamics grows out of three prior activities:

1. traditional management meaning the way people have managed families or businesses. The greatest strength of traditional management lies in the tremendous data base; and most of the data exists in people's heads

2. feedback systems (cybernetics, study of communication and control in living organisms or machines)

3. computer simulation.

Reality however is too complex to be represented wholly in its form; a model is significant to predict the effect of certain decisions and interferences on the reference modes if all the relevant elements and relationships are included in the model and correspond to those in the real world.

System dynamics has been applied successfully to a variety of industrial, social, economic, biological, psychological and engineering problems.

Problems viewed from the systems dynamics perspective is first seen in terms of graphs of one or more variables over time. The dynamic thinking of the relations is then represented by any graph with interconnected loops called feedback loops, i.e., loops of causes and effects, which are the key in systems dynamics. All of these problems can be studied by aggregating the individual "events" into a continuous flow and examining this flow in the context of the (continuous) variables that affect it and are affected by it. Typically, these variables form a "closed loop feedback system," where X affects Y affects Z affects X. Feedback systems exhibit behavior that cannot be predicted by looking at the components of the system in isolation (see figure 6).

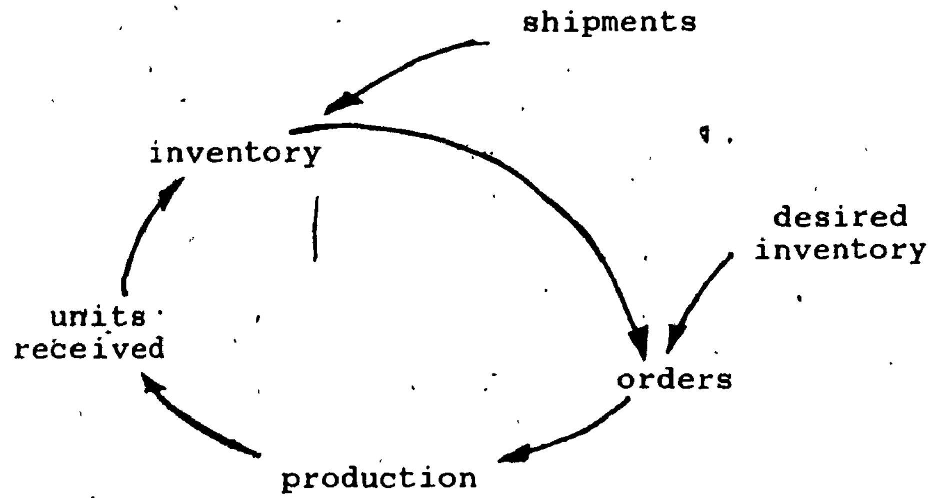


figure 6. Simple inventory feedback loop [25]

Shipments deplete inventory, so as it drops below some desired level, orders are placed with producers, goods are received and inventory is brought back to the desired level and thus a feedback loop is established.

Real-life systems frequently contain closed feedback loops that generate counter-intuitive behavior patterns that would not be explained by an open cause-and-effect analysis.

To define more finely the model in its structure, a sign corresponding to the type of influence is allocated to each relation:

1. (+) sign: if the influenced, variable B varies in the same direction than the variable A

which is the cause of this variation.
If A goes up, B goes up

2. (-) sign: if the influenced variable B varies in the opposite direction of the variable A which influences the variable B.

The feedback loops can be categorized into two types, the negative and positive feedback loops:

1. positive feedback loop; a positive feedback loop amplifies deviations and disturbances, is growth producing or self-reinforcing. When the loop is composed only of connections with a "+" sign; this means that if a variable is modified in the direction, all the other variables of this loop will vary in the same direction to influence in return the first variable and then emphasize the variation of this loop. A positive loop contains also an even number of negative casual links (see figure 7)

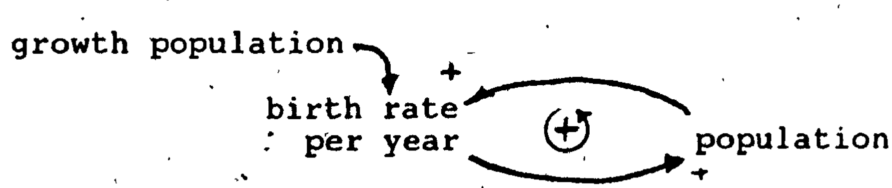


figure 7. Positive loop: population and births rate [25]

If the birth rate per year increases, the population increases or goes in the same direction, i.e., plus sign; and ~~if~~ the population increases, the birth rate per year increase or go in the same direction. Note that if the birth rate per year decreases, this means that birth rate increases less rapidly and then the population increases less rapidly giving also a positive loop. This is a loop that describes an "explosive" behavior. It describes "snow ball" effects (see figure 8).

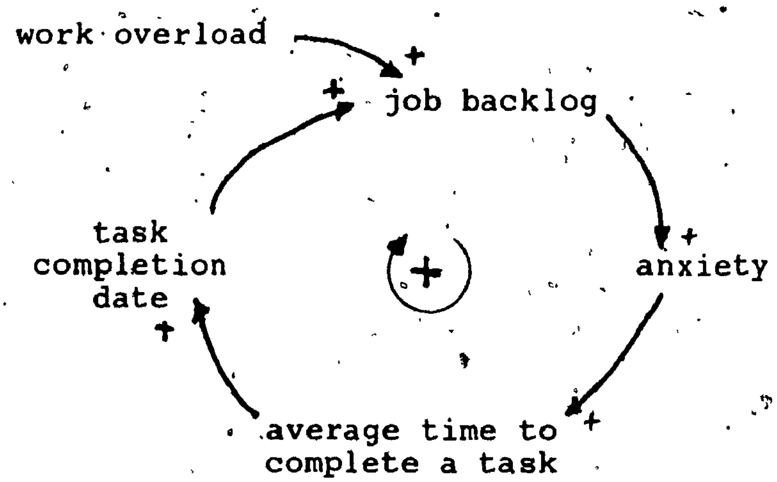


figure 8. Positive loop: the job backlog and anxiety [25]

In this example,

1.1 if the work overload goes up, the job backlog goes up or goes in the same direction (plus sign)

1.2 and if job backlog goes up, the anxiety goes up (plus sign)

1.3 and if the anxiety goes up, the average time to complete a task goes up (plus sign)

1.4 then, if the average time to complete a task goes up, task completion date goes up (plus sign)

1.5 and finally, if the task completion date goes up, the job backlog goes up or in the same direction (plus sign).

An increase of job backlog was assumed at the beginning and at the end of the loop, the job backlog goes up; this proves that it is a positive loop (i.e., in the same direction). If any other variables are taken to define the loop, the result must be the same.

If there is a positive loop in a system, three types of behaviors can be generated:

1. Unstable equilibrium; this means that in the studied conditions, the system is in equilibrium but with the least perturbation of these conditions, the system will be in one of the two next behaviours
2. "explosion" (exponential growth)
3. exponential decrease

2. <u>negative feedback loop</u>

The second loop describes a behavior completely different. The possible variation of an element is opposed in return by a variation of other elements in the opposite direction.

A negative feedback loop attempts to negate any deviation from some equilibrium or goal state in order to stabilize, equilibrate or regulate the system. It is also called a goal seeking loop. A negative loop contains an odd number of negative causal links affected with a (-) sign (see figure 9).

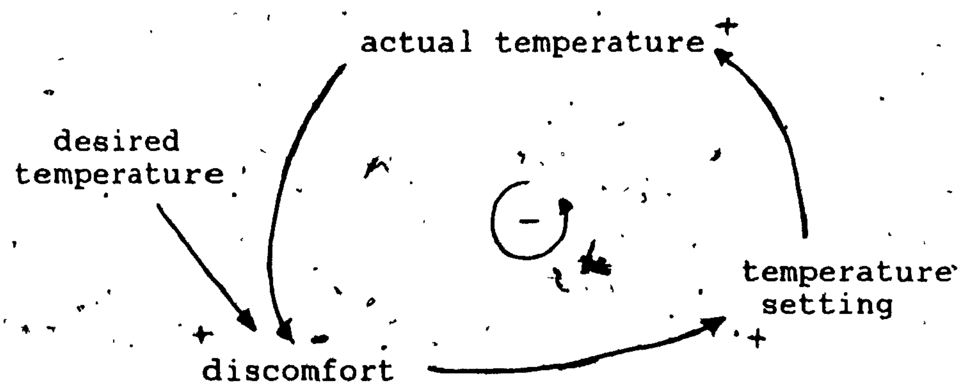


figure 9. Negative feedback loop: goal seeking [25]

In this example,

2.1 if the discomfort goes up due to an increase of the gap between the desired and actual temperature, the temperature setting goes up (plus sign).

2.2 then, if the temperature setting goes up, the actual temperature goes up or in the same direction ;

2.3 and then if the actual temperature goes up the discomfort will go down or in the opposite direction, i.e., minus sign, because the gap with the desired temperature goes down.

The problems of senior management, for example, generally do not involve individual sales transactions or particular machines, but rather aggregate revenue and production rates. The government resolves issues not on a person-to-person basis, but rather considers the population as a whole and the future implications of each decision. An engineer is not concerned with the behavior of an individual molecule, but rather with the performance of the machine as a whole.

These loops make that the system will be finally on equilibrium. The typical behavior is a damped oscillation towards an equilibrium.

The modeler remembers these major points in conceptualization to reduce the complexity of the problem definition and conceptualization:

1. focus on the problem not on the system
2. understand the physical processes in the system that are relevant to the problem
3. understand what are the perceptions of those processes
4. understand how these perceptions combined will create pressures that influence the physical processes.

Conceptual stages in modeling process can be summarized schematically as follows:

stages	concerns
Problem definition	Context; symptoms Reference behavior modes Model purpose
Model conceptualization	System boundary Feedback structure The casual diagram or the connections graph (of influences) of components one with the other is designed.

Model formulation	Representation according to the software
Simulation	Model behavior
Evaluation	Reference behavior modes on graphic output produced with the time on an axis and variables on the other

The element itself can be considered as a system too. Simulation means experimentation with models by changes in elements or relationships in order to understand the behavior of the system or compare the meaning and values of different strategies. Equations, and variables computed by them, are classified into different types: levels, rates, and auxiliaries.

System dynamics technique is simple and can be used by non-computer specialists. The software developed is called DYNAMO which is a continuous simulation language, which means that it computes the evolution over time of a collection of associated elements sharing a common purpose or a number of variables which depend one another. Continuous models are useful when the system in question depends more on aggregate (average, continuous) flows than on the occurrence of single, discrete events.

The DYNAMO's basic principles is summarized hereafter: variable types, notation conventions, initialization, built-in functions and output.

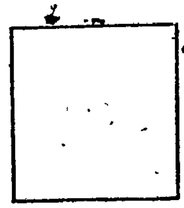
The basic tool of continuous simulation (beyond simple arithmetic) is the process of integration. Integration appears everywhere in nature and is essential to represent the process of change in real systems.

For instance, in a construction project described in Dynamo representation, one equation might describe the accumulation of material ordered which is called the "level"; another equation might describe how the level or the accumulations of material ordered changes during each short period of time depending on the difference between the flows that drain or fill a level which are called rates; for example, there is a rate of material delivered and the rate of material orders received. The terms "level" and "rate" are intended to invoke respectively the image of the level of a liquid accumulating in a tub and a valve. The valve controls the quantity of "liquid" flowing in the pipe. Other equations would compute the variables in the rates equations.

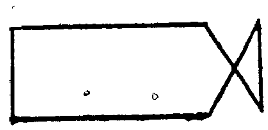
Variables that are neither accumulations (levels) nor flows (rates) are classified as auxiliaries. Auxiliaries are the building blocks for levels or rates; they are used to represent a more complicated expression in a rate or level equation, for example, the desired workforce, the quality of work, the time remaining.

Conventional symbols are used for diagraming the equations (see figure 10):

Level:



Rate:



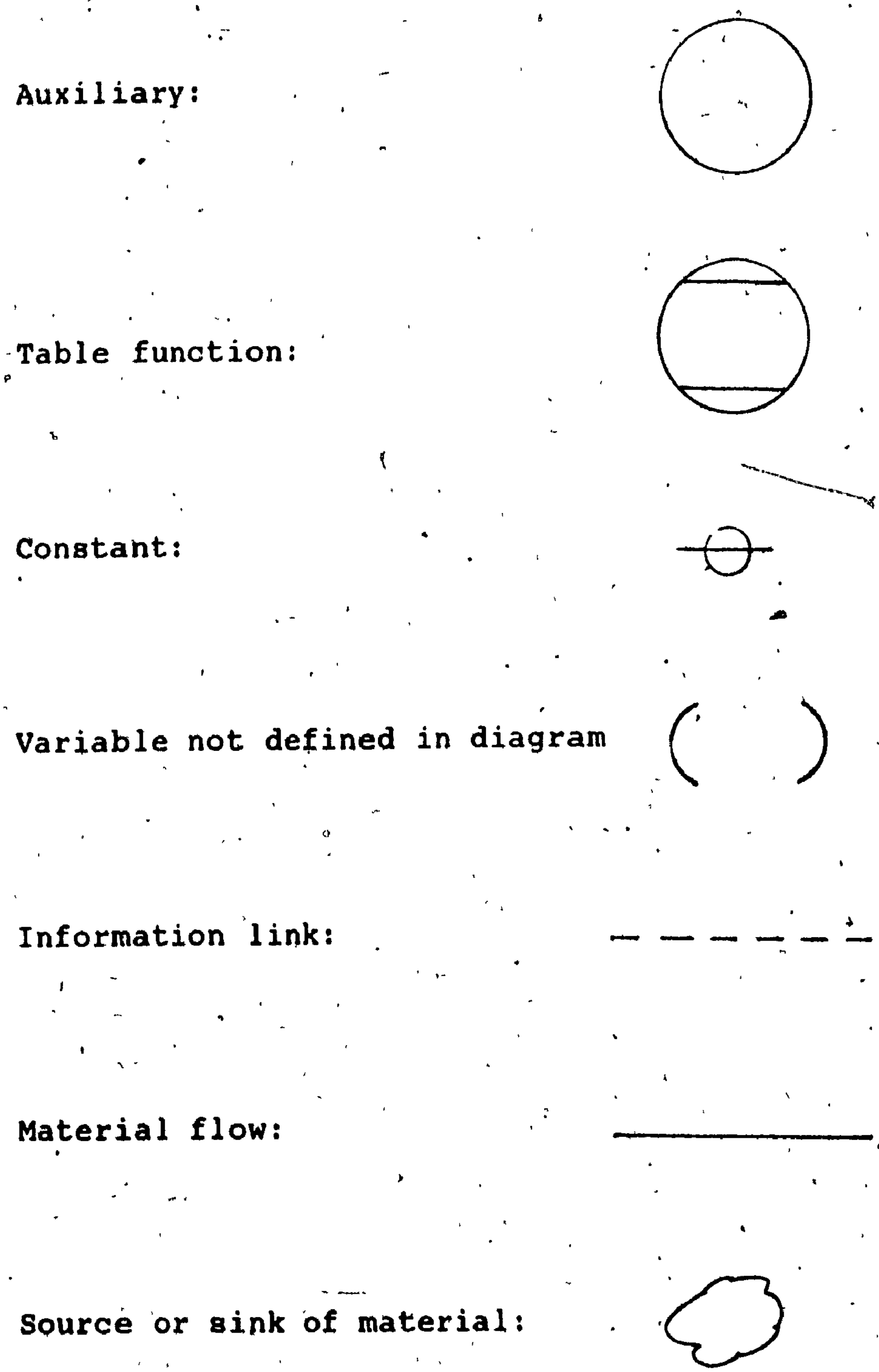


figure 10. Symbols for flow diagrams

These equations are complemented by:

1. constants

1.1 constants (C), alternative indications of a parameter

1.2 initial value (I), used to supply and initial value to one or more levels

1.3 model parameter (P), is used in one or more active equations (e.g., the value of a delay).

1.4 binary value (B), meaningful values with 0 or 1 used to select one or more formulas for a variable. Typically, the binary value multiplies one of the formulas and (1-binary) multiplies the other.

2. tables to describe the variation of one variable in relation with another variable;

3. model operation specifications;

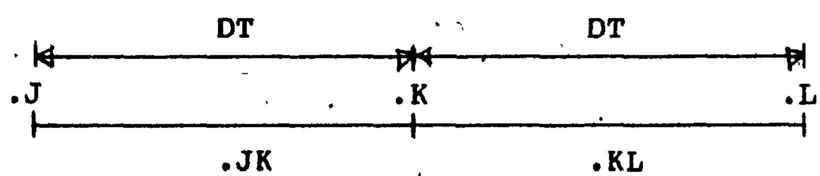
4. output instructions to make up the body of a dynamo model. Dynamo outputs show all the desired variables of the model that evolve over time.

The order of calculations moves foward through time in discrete steps. The length of the timestep for computer calculation is specified in the model by the parameter DT, i.e., delta time.

First of all, the level variables are computed from one instant to the next from their own value in the previous timestep; then, rates and auxiliaries in the level variables are computed in each previous timestep from other variables already computed.

The dynamo language includes time subscripts on each variable that remind the modeler how dynamo is stepping over time:

1. the previous time where calculations have been made is designated ".J"
2. the present time of the calculation is designated ".K"
3. the next time at which calculations will be made is designated ".L".



"MOMENT": previous now next

To resume, lets see equations for material ordered:

```
L    MTLODR.K=MTLODR.J+DT*(ODRMTL.JK-DELRML.JK)
N    MTLODR=0
R    ODRMTL.KL=REQMTL.K/ORDY
```

```
P      ORDY=4
R      DELRML.KL=MTLODR.K/DELDY.K
A      DELDY.K=TABHL(TDELDY,QDSD.K,0,1,.2)
T      TDELDY=20,20,20,16,14,8
```

```
Where  L means a  Level       equation
       N means an iNitial     equation
       R means a  Rate        equation
       C means a  Constant    equation
       A means an Auxiliairy  equation
       T means a  Table       equation
```

The level equation has the form:

amount(now) = amount(earlier)+ elapsed time x net flow

and means that the material ordered at the current value of simulated time (.k) is equal:

1. to its value at the previous timestep (.J) which has the initial value of 0, (then you can compute its value at some later time)

2 +.Delta Time (the size of time step) times the difference between the orders rate of material and the delivery rate of material (both timescripted.JK).

The level is the subject of integral calculus and integration.

The rate variables in the level equation are computed at the present time for the interval from K to L. For instance,

1. the first rate equation R ODRMTL.KL=REQMTL.K/ORDY

means that the orders rate of materiaL from K to L is equal to the number of requisitions of materiaL divided by the order delay.

2. The next rate equation means that the delivery rate of materiaL from K to L is equal to the level of materiaL order at the present time divided by the delivery delay which is an auxiliary equation that is a table function in relation with the quality of design of shop drawings in the present time. The use of double timescript .KL or .JK means that the rate is assumed constant over the timestep.

The initial values for every level may depend on constants, auxiliaries or rates. The arithmetic operators "+,-,*,/" can be used. The names may contain up to seven characters.

Dynamo language includes many functions to provide a convenient notation for special relationships between variables. The most frequently used is the TABLE function. We can observe that the table look-up function defines the relationship between the quality of design of shop drawings that varies from 0 to 1 by 0.2 increment and the delivery delay that varies from

20 to 8 weeks. The dynamo language can interpolate or extrapolate to find the value. There are many table functions in a model to define the relationship between variables.

Other functions provide a convenient notation for specifying a special relationship between variables. The most frequently used are:

Function	Name & Comments
1. delays:	DELAY1(IN,DEL) IN = input DELAY3(IN,DEL) DEL = average delay time SMOOTH(IN,DEL) the change is smooth compared to a step change
2. table functions:	TABLE(TAB,X,XLOW,XHIGH,XINCR) TABHL(TAB,X,XLOW,XHIGH,XINCR) TAB = name of the table X = independent variable XLOW and XHIGH=lowest or highest value in the range of the independant variable XINCR=increment between value of the independant

variable

3. logical

functions:	MAX(P,Q)	P if P > or = Q
		Q if P < Q
	MIN(P,Q)	P if P < or = Q
		Q if P > Q
	SWITCH(P,Q,R)	P if R = 0
		Q if R <>0
	CLIP(P,Q,R,S)	P if R > or = S
		Q if R < S

4. test

inputs: STEP(HEIGHT,START)

NOISE()

PULSE(HEIGHT,FIRST,INTVL)

HEIGHT is the step or pulse height

START = time of the step

FIRST = time when the first pulse occurs

INTVL = interval between pulse

5. arrays: "array" variables provide repeated structures which can be used in any statement type. An "array" variable is a collection (or set) of ordinary variables that is given a single name. The ordinary variables (called "elements" of the array) can be designated individually by adding subscripts to the array name.

Identical statements could be written to separate variables, or a single array variable could have many elements. Each element in the array could have a different value.

An array variable is identified as such by the presence of a subscript (set off by parentheses) after the variable name. When an array variable is used in a statement, the value(s) of the subscript(s) determines which elements of the array are used. The subscripts may be integers, element names, or "FOR" variables; expressions, using addition and subtraction are also valid with certain restrictions.

6. mathematical functions:

6.1 EXP(A) A=input to the function

6.2 SIN(A) A=input to the function

6.3 COS(A) A=input to the function

6.4 SCLPRD(vec1,first-el1,last-el1,vec2,first-el2)

The scalar product function computes the sum of a scalar, or single-value quantity of the products of corresponding elements of two vectors. Where the general rules for arrays are:

1. vec1 is the first vector
2. first-el1 is the index of the first element of the first vector
3. last-el1 is the index of the last element of the first vector
4. vec2 is the second vector
5. first-el2 is the index of the first element of the second vector.

6.5 SUM(array) computes the sum of all the elements of array, however many dimensions it may have. SUM can also be used to process an (entire) vector.

7. For: when a statement applies to more than one element of an array, one or more FOR (indexing) variables must be used in place of integer subscripts to specify which elements should be used.

8. spec: at the end of the model a SPEC statement specified essential parameters for the simulation:

DT -the interval between TIME.J and TIME.K

LENGTH -the value of TIME when the run is to be terminated

SAVPER -the interval of TIME between the saving of results for later comparative output in printing or plotting.

The model should be a tool that allows the management to experiment with policies for improving management and for testing other policies in changing the table functions or constants in a rerun mode.

CHAPTER IV

REVIEW OF RELEVANT LITERATURE

In this chapter, two relevant models are presented. The first is the development of a system dynamics model in the area of software development project management entitled " The dynamics of software development project management: an integrative system dynamics perspective", a thesis developed by Mr. Tarek K. Hamid for the degree of doctor of philosophy at the Massachusetts Institute of Technology in January 1984. A study of this research was done to understand the cause-and-effect interactions and to learn some technics to describe in equations some processes that reflect the reality.

The second relevant literature presented is a small model also in research and development which has about thirty equations. This literature is in the book published in 1983 by the MIT Press and entitled "Introduction to System Dynamics Modeling with Dynamo" and developed by Mr. George P. Richardson. It is a basic research approach for this study because factors like progress, workforce, schedule are also the main factors in a construction project.

As part of the planning function, the principal is that management determines the workforce level necessary to complete the perceived tasks remaining within the schedule completion time. To manage human resources, this literature presents two levels of workforce: the new workforce that becomes experienced after a period of time and the workforce with experience that are transferred on another project if they are not required. This approach reflects more the reality compared with only one level of workforce because newly hired workforce is less productive than the workforce with experience. In the Tarek's model, there is daily manpower used for training and there is also a ceiling on new hires. The model defines also full-time equivalent workforce because in many organization software, developers are assigned to more than one project in order to better identify the desired ceiling of workforce and then the workforce level sought.

The software production has four primary activities: development which includes the design and the coding, quality control to detect design or coding errors, rework and system testing. A daily manpower is identified for each activity; the remaining bulk of manpower resource that is not working in training or quality assurance activity, is allocated to software development which is defined in terms of a number of tasks. The rate at which the software is developed is function of manpower and on the productivity of software developers which is a function of a complex set of factors and principally:

1. a potential productivity which is affected by the learning and an average nominal potential produtivity which is affected by the workforce experienced and a mixed productivity due to the new and experienced workforce;
2. a multiplier to productivity due to motivation and communication losses which are affected by the communication overhead and the actual fraction of a man-day on project. An increase in communication and motivation losses implies a lower multiplier.

At this stage, the model introduces the notion of schedule pressure because it was observed that there was less severity in quality assurance as work pressure increased to meet delivery schedule. The schedule pressure is formulated as the ratio of:

$$\frac{\text{the gap between the total effort perceived to be still needed to complete the project and the total effort remaining in current plan (man-days)}}{\text{total effort remaining in current plan (man-days).}}$$

The schedule pressure affects the planned fraction of manpower for quality assurance and the motivation mechanism. Positive schedule pressures arise whenever the project is perceived to be behind schedule; this means that the effort perceived needed to complete the project is greater than the total effort actually remaining, tending people to work harder to bring it back on schedule by compressing their slack time and/or working overtime until a maximum boost in man-hours taking into account the threshold due to exhaustion.

The model formulates also equations to consider generation, deletion and correction of errors under nominal conditions or under schedule pressure. The error generation rate includes two sets of factors:

1. the organizational factors which concern the use of structured technique, the quality of staff;
2. the size and complexity of the system and language.

The error generation density, work efficiency and error-type influence the quality of manpower needed to detect an error. As the majority of errors are detected through the quality assurance activities, they are reworked at a rate function of the manpower committed to the rework activity and the rework effort per error.

This model includes a section for the planning: the time remaining is formulated as the gap between the schedule completion date and the number of working days elapsed. The indicated workforce to complete the project at the schedule completion date is formulated in dividing the value of man-days remaining by the time remaining.

If the indicated workforce level is lower than the number of full-time employees, more people will be hired; if the opposite is true, excessive employees will be transferred. But because hiring decisions are determined not only on the basis of scheduling considerations but also by the stability of the workforce, a relative weighting is measured between the desire for workforce stability and the desire to complete the project on time. This concludes the model presentation including four sectors: production, planning, human resource management and control.

The other literature that is interesting for the purpose of this thesis is the Richardson's model; the model available was a simple model that is developed around these levels and rates by considering in turn the following small sectors:

1. real progress
2. undiscovered rework
3. perceived progress
4. effort perceived remaining
5. hiring
6. scheduling.

In this model, the progress is called "apparent progress". So, simply, the apparent progress is defined as a function of the workforce and the productivity (tasks/person/month) which is a constant in order to have the most simple model. The progress is called "apparent" because it is divided in two different kinds of progress: real progress and undiscovered rework; when workers perform tasks with a given productivity most of the work is done correctly but a small portion of the work is done with errors. A level for the cumulative real progress accumulates work done satisfactorily and another one accumulates the generation of undiscovered rework. After a certain time, the work classified undiscovered rework will be discovered and then the level of cumulative undiscovered work is reduced. In this simple model, the time to detect rework is a constant but it is explained that it seems reasonable to use a non-linear function in assuming that it becomes shorter as the project appears to near completion.

The cumulative perceived progress is consequently the addition of the cumulative real progress and the cumulative undiscovered rework. The tasks perceived remaining are the variance between the initial quantity of tasks to realize and the cumulative perceived progress. The effort perceived remaining is a function of the tasks perceived remaining and the perceived productivity which is a weighting between a constant productivity and a "real" productivity that is function of the fraction of work done satisfactorily during a period of time. With the effort perceived remaining (in man-days) and the workforce, the time perceived required to complete the project is defined. In adding the time perceived required to the actual time, the indicated completion date is defined and could modify the schedule completion date.

The workforce is a function of the net hiring rate which is a function of the actual and the workforce sought; the workforce sought being a function of the effort perceived remaining already discussed and the time remaining between the schedule completion date and the actual time during a simulation run.

CHAPTER V

THE MODEL PRESENTATION

5.1 The Model Definition

The model consists of the assembly of three subsystems:

1. the design subsystem which represents an assembly of three important sectors (workforce, progress and scheduling). The design subsystem describes how drawings are produced
2. the procurement subsystem for procurement progress. The procurement subsystem simulates requisitions, purchase orders and delivery of material, starting from the design's evolution
3. the construction subsystem which also represents an assembly of three important sectors (workforce, progress and scheduling). The construction subsystem describes the physical progress of the project, taking into account the two previous subsystems (see figure 11).

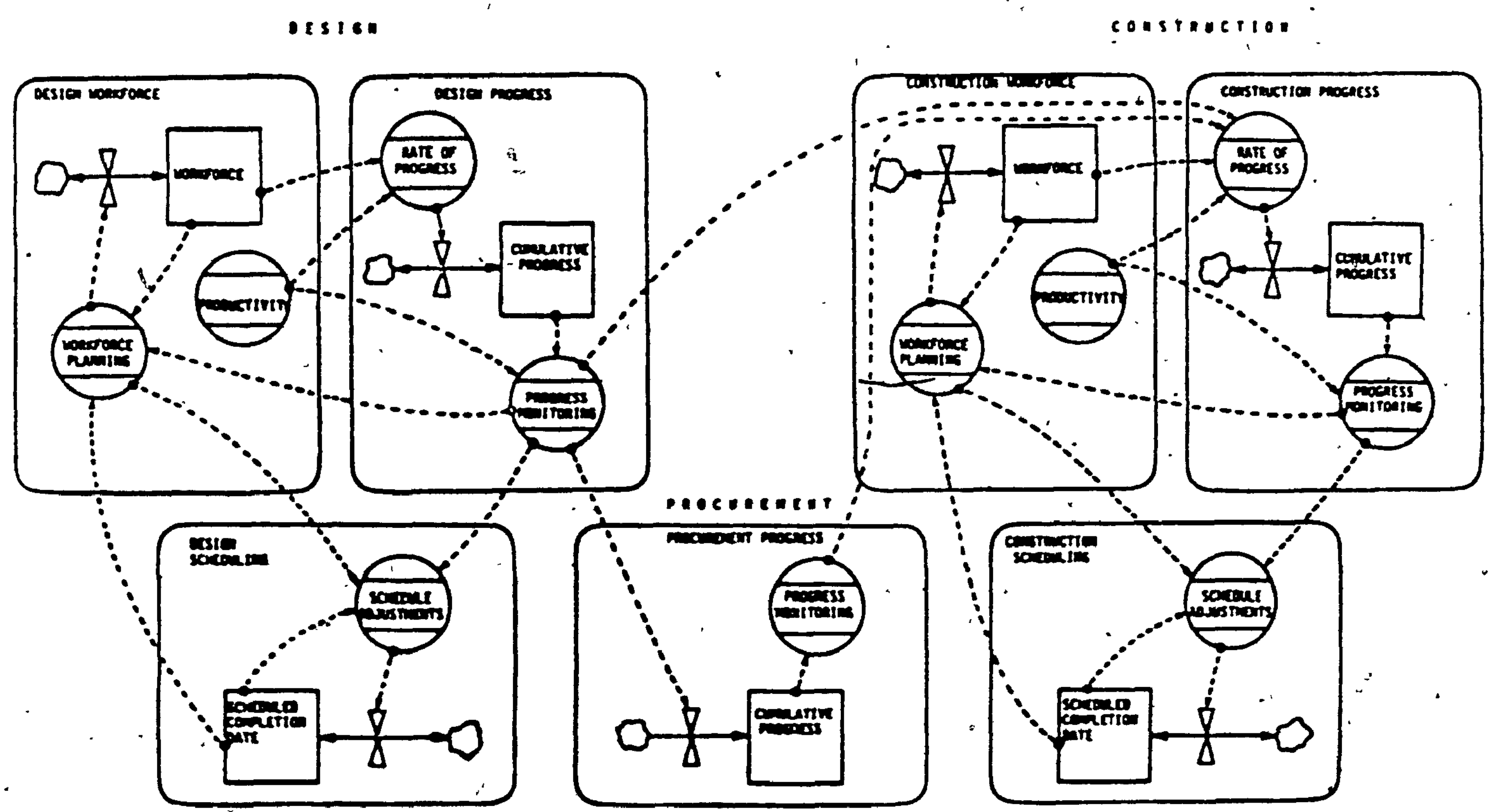


Figure 11. Design, construction and procurement **subsystems**

Even if the structure of the construction subsystem is similar to the design subsystem, each subsystem has specific modules to differenciate design from construction for workforce, schedule completion date and apparent productivity. In this study, the main causal loop is based on the Richardson's model already presented and is detailed to adapt the model on specific points about the design-construction process. In these subsystems, the manager estimates the remaining work at each simulation step, and forecasts the delivery date. From these estimates, the manager may shift the workforce on another project, or may take people from the company's other projects. It may also be necessary on occasion to change the delivery date. The procurement subsystem presents specific formulations that were not in other models studied; this subsystem was included in the model because the delivery of material on site at the right time is essential for the success of a construction project. In many projects, a lack of material will cause disruption and overrun.

The model is composed of matrix equations defined as "array"; the design, the procurement and the construction processes are divided in five specialties which group the sixteen specialties:

1. civil
2. mechanical
3. electrical
4. architectural (exterior work)
5. interior (architectural work inside the building).

The models developed in research and development that are detailed in the previous chapter do not include matrix equations. Here, the advantages of using matrix equations are in summary that, in the design and the construction subsystems, the model controls these criteria for each step during a simulation run:

1. when a specialty can start considering the progress of the succeeding specialties
2. when a specialty must stop its work temporarely considering the progress of other specialties
3. when a specialty will be able to complete its work considering the progress of other specialties

In order to evaluate from different design, procurement and construction overlap schemes, the optimal solution that minimizes duration, cost, and maximizes quality and productivity, the user can change or indicate these variables which are "constants":

1. desired duration of each specialty in the design

and construction processes

2. construction starting time (civil work)
3. procurement starting for each specialty
4. change that can shock the design and the construction processes at any time during the simulation

5.2 The Design Subsystem

The design, procurement and construction are proceeding in sequential packages. An equal number of drawings is assumed for each floor.

First of all, preliminary engineering defines (besides the type and position of shearing walls, elevator lifts, curtain walls, beams, etc.), the non similarities, like the different types of floors, typical cross sections, etc..

After the approval of the preliminary architectural sketch, the architect will detail his drawings sufficiently to allow the structural engineer to design the building for the foundation and the infrastructure. After a short period, the electrical engineer and the mechanical engineer progress in the design in coordination with one another and with the interior designer. The final design consists of finalizing the details of each similarity.

The architect starts with a certain number of designers, but he will be obliged during the design process to increase the number of designers in each specialty. The hiring is represented by the "hire rate" and this is cumulated in a level, the new workforce in design. "After an assimilation period, this workforce becomes experienced". The total distribution of resources is done trapezoidally during the design life cycle as required in practice.

The ratio of design effort perceived remaining to the time remaining in design is multiplied by the required trapezoidal distribution factor that varies with the progress of design to determine the indicated workforce in design.

The design workforce sought will be measured also in regard of the indicated workforce and by the ceiling to design workforce. If there are too many resources, the firing process or the transferring rate for design will start by the new workforce. The new workforce with the experienced workforce represent the total design workforce that will realize the design according to the apparent productivity defined in function of a gross productivity that can be modified by these factors:

1. the schedule pressure effect on productivity in design [31]
2. the learning effect on productivity [10]
3. the effect of job size on design [3]
4. the productivity multiplier due to the feedback required between specialties

In the fast-tracking case, a construction work breakdown structure is established according to scope configuration management and constructibility, which means that after preliminary engineering, the building project is packaged to be designed the way it is going to be built.

5.3 The Construction Subsystem

This subsystem has some similarities with the design process; the general contractor plans his workforce sought in function of the schedule completion date stipulated in the tender document. To achieve this, the hiring of workforce is represented by the "hire rate" and this is cumulated in a level, the new workforce in construction. "After an assimilation period, this workforce becomes experienced" [31]. The total distribution of resources is done trapezoidally during the construction life cycle.

The construction effort perceived remaining divided by the time remaining and multiplied by the required trapezoidal factor that varies with the progress of construction, will determine the indicated construction workforce.

The construction workforce sought will be measured also in regard of the indicated workforce and by the ceiling to construction workforce. If there are too many resources, the firing process or the transferring rate for construction will start by the new workforce. The new workforce and the experienced workforce represent the total construction workforce that will realize the construction according to the apparent productivity defined in function of a gross productivity which can be modified by these three factors:

1. the schedule pressure effect on productivity in construction [31]; workers could work on overtime if the manager is willing to do overtime
2. the learning effect on productivity [10]

3. the effect of job size on construction [3]
4. the productivity multiplier due to the workforce required taking into account the progress of inter-connected specialties. The manager could work on overtime (overtime to accelerate due to the progress of the specialty or the preceding specialty)
5. the effect of the area workload [3]
6. the lack of material or equipment.

System dynamics models can then help us to understand the productivity phenomenon in construction projects.

In the model, special attention is given to design and construction productivities because differenciation between design and field labor is essential for better strategic planning and project control. Relations between quality and productivity can be analysed; a better productivity has a tendency to improve quality and most of the time poor productivity means poor quality. In a fast-track project, the degree of overlap on design-construction has an effect on productivity and consequently on quality.

5.4 The Procurement Subsystem

When the management decides to start the procurement process, requisitions of material are submitted in regard to the potential number of requisitions which is a function of the design progress; then purchase orders of material are issued to the vendors who will prepare shop drawings for approbation by the engineers before starting the fabrication. In consequence, the quality of design of shop drawings will affect the delay of delivery of material and could postpone the duration of the construction. The quality of shop drawings is also a function of the average quality of design prepared by the consultants.

A lack of material affects the progress of work. In practice three types of material have to be considered: material with long lead time delivery, material in short supply and material fabricated in cycling. If the real quantity of material on site is less than the theorical quantity of material needed, there will be a reduction of the apparent productivity and of the quality of the construction.

5.5 Project Control Baselines vs Behavior Modes

The model concentrates upon aspects of design and construction project dynamics that are within the control of people on the project. The outstanding features of the system boundary are:

1. the project definition (drawings or construction jobs to be performed)
2. the project personnel (new and experienced designers or workers)
3. the hiring and terminations (person per week)
4. the progress (drawings or construction work completed per week)
5. the productivity (drawings or construction work per person per week)
6. the schedule (completion dates of design and construction)
7. the quality (quality of design and construction)
8. the rework (design and construction work to redesign or rebuild)
9. the procurement (availibility of material on site)
10. the cost (dollars required to realize the project according to the policy)

Any project is defined by a certain number of parameters like time, cost, resources, rate of productivity, etc. and those parameters can be associated with the design and construction behaviorial modes of the project to become the project control baselines. A baseline is a control pattern on a time scale. Some of the control patterns identified in the model are:

1. the duration of the project
2. the human resources to be used on the project
3. the productivity of the project
4. the total cost of the project
5. the time remaining to scheduled completion date
6. the perceived progress.

When those modes of behavior dependent on specific policies have been established by the simulation process according to a specific strategy, they become the project control baselines of the project. Project control baselines are indicators that are necessary to evaluate performance deviation.

One of the most important behaviors is the S-curve. The sum of the three separate areas of effort (design, delivery of materials and construction) gives the S-curve for value of work done for the project as a whole. The S-curve for value of work done always follows the same path. With a different organization, and a different type of project, the S-curve will also be somewhat different, but each time the S-curve follows substantially the same path (see figure 12).

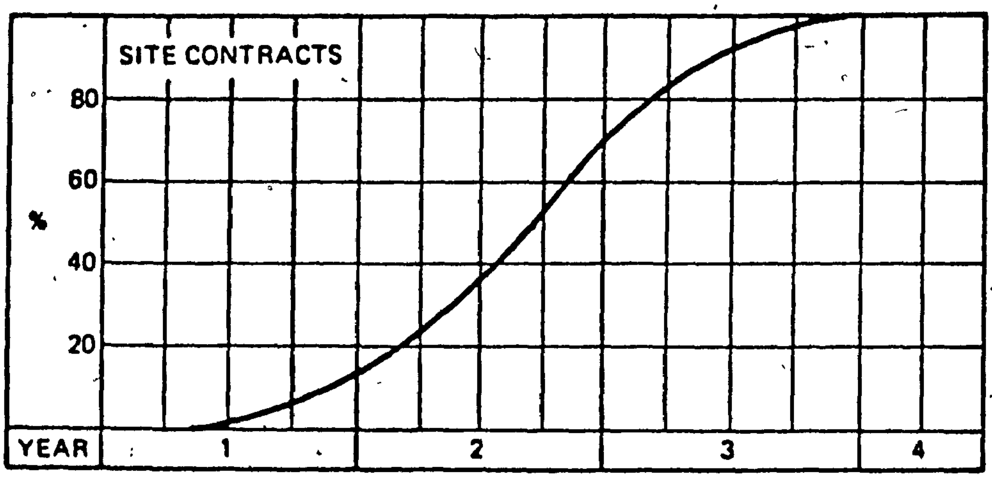


figure 12, "S"-curve

5.6 Basic Causal Loops for the Design and Construction Subsystems

The design and construction subsystems are each composed of one dominant loop: a negative loop (see figure 13). This major negative loop has the goal to realize the project: as the workforce goes up, the progress rate and the cumulative progress go up, then the tasks perceived remaining go in the opposite direction; when the tasks remaining go down, the effort remaining, the indicated workforce, the net hiring and the total workforce go in the same direction.

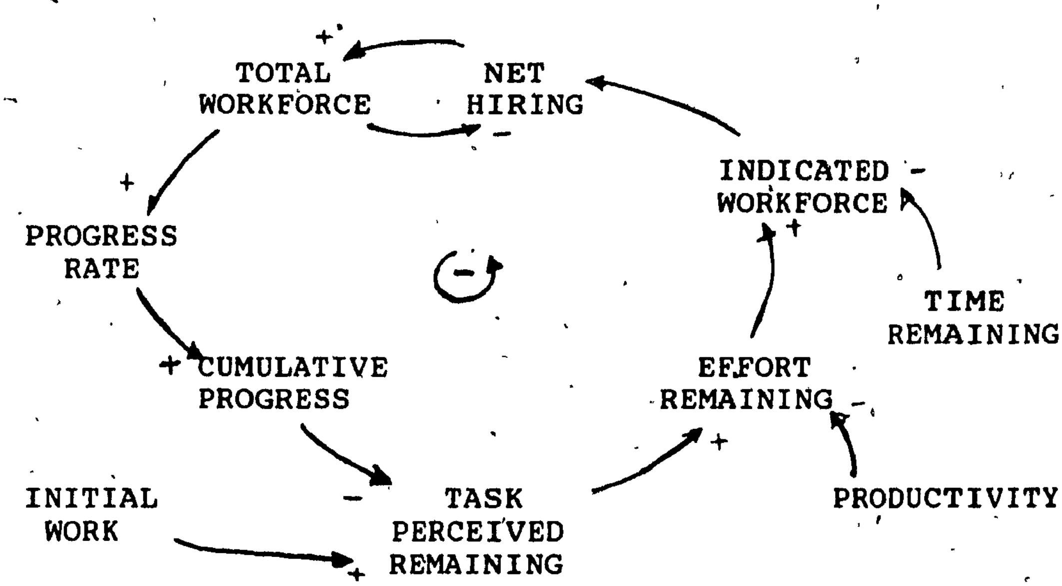


figure 13. Basic causal loops for the design and construction subsystems [25]

There are other negative feedback loops; for instance, when it is recognized that the perceived progress is behind schedule compared to the calibrated progress, the schedule pressure increases and then the workers and the management will increase the work rate to be on the target date, thus reducing the pressure on the schedule (see figure 14) [31].

At the same time, the schedule pressure will decrease the quality of construction and then will reduce the rate of construction not needing rework and therefore maintains the slippage of construction schedule and the schedule pressure on workers; this is the positive loop (see figure 14) [31].

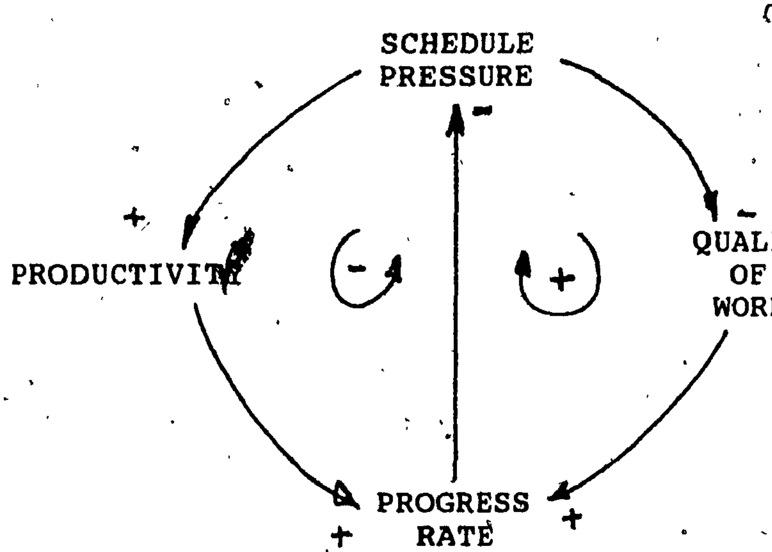


figure 14. Negative and positive loops in the design and construction subsystems

5.6 Description of the Model Equations

Each equation is a matrix equation meaning that the equation is related to five specialties for the design and the construction processes: civil, mechanical, electrical, architectural and interior (including interior architectural work). For instance, the variable QD(DI) where QD means the quality of design and (DI) means that there is a quality factor for each of the five specialties. So, if the model has about 350 variables, this means that 1750 values are identified, for each timestep in a simulation run. An equation could also describe relations between the specialties; to be able to define these relations, a sub-matrix is defined for a specific specialty and then, it is possible to define the other specialties from that specialty. For instance, as it is defined in this model, (DI) means the five specialties and (DI3) means the mechanical specialty; then, the Dynamo language allows to say that:

1. (DI3+1) is the electrical specialty
2. (Di3+2) is the architectural specialty
3. (DI3+3) is the interior specialty
4. (DI3-1) is the civil specialty.

5.6.1 Description of the Design Subsystem

5.6.1.1 Quality in Design

In the design subsystem, the quality is a smooth function meaning that a change in the quality of design will not be recognized immediately by the model, but over a period of time. The quality delay value is set to five workable weeks; it is assumed that this value is the most realistic value. Essentially the quality of design is not a constant but a variable that changes smoothly with the perceived progress of design. The non-linear value of the quality represents the quality of design due to the motivation of designers. At the beginning, everybody wants to do a perfect job, but the motivation of designers in each specialty will decrease with time; in the second phase of the project, the management requires more effort to be on schedule; when the project is close to the end, the designer's motivation decreases due to the stress of seeking a new job or to be placed on another unknown project [27].

The data used for the quality of design also indicates the quality seeking goal for the management. The same shape could be drawn but at a lower level to show a lower quality due to a management that does not require a higher quality.

A table indicates the values that give the shape of the quality of design. A value of 96% is assumed at the beginning of design process; there will be a decreasing, then an increasing to meet the target date and, at the end, a small decreasing due to a decreasing in motivation (see figure 15). In system dynamics, an equation defines a variable and evaluates the most appropriate value according to the state of the system during a run. From this given table, the model will interpolate the value of the variable in relation with the progress of design. The Dynamo language interpolates a quality value if the progress is within the range specified; if in a simulation run, the value is highest or lowest than the specified range, the model takes the highest or the lowest value given in the equation.

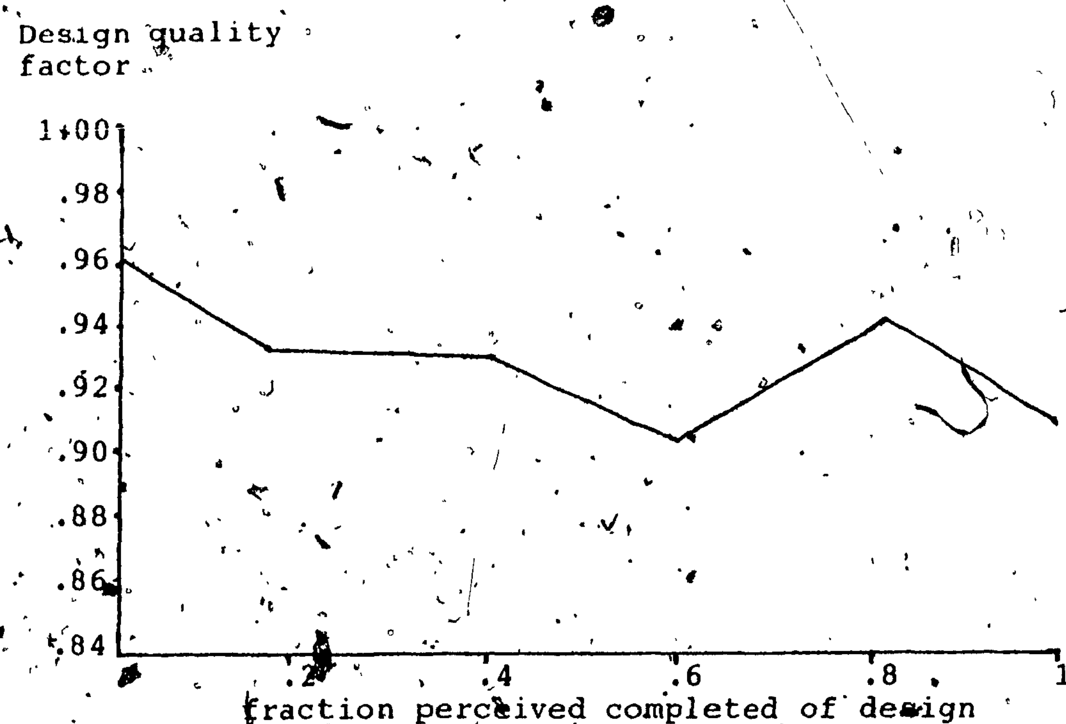


figure 15. Quality of design

Anyhow, the quality of design is affected by the experience of workforce, by the schedule pressure effect on quality to meet the target date, by the effect of work added during the design that has an effect of demotivation on the designers to produce quality work.

As described hereabove, the quality of design is affected by these factors:

1. the effect of work added;
   this quality multiplier introduced in this study, applies only when there is a notice of work added.

The motivation multiplier goes down when the ratio of total work added to the total initial work goes up. The more work is added, the greater the ratio, the less is the motivation.

The effect of work added on quality due to motivation is greater as the design perceived progress goes up; this is described in a table: until 20%, the effect is zero, from 20% to 80% perceived progress the factor varies from 0.0 to 0.65 and then goes up to 1 when the progress is 100%. So, at the beginning of the project (less than 20%), there is no negative effect on motivation even if there is work added (see figure 16). These values are the most reasonnable values assumed. It should be understood that the analysis of simulations is not only based on the result of a simulation but also on the results compared with another policy.

2. the effect of workforce with experience; the quality of design is affected by the experience of workforce; the more there are designers with experience in regard to new workforce, the greater is the factor for the quality of design [31]. The word "experience" means the experience on the

present project. The minimum quality is set to 91% even if there is only new workforce. This factor goes up from .91 to 1 when designers become more experienced (see the figure 17).

3. the effect of work added on quality in design;
as the work added goes up, the motivation of workers goes down until a limited point set to 80% in the model. The work added effect is measured in taking into account the ratio of the cumulative number of drawings added to the initial number of drawings (see figure 18); also, this multiplier could have a non-zero value only if there is a timestep with work added. One of the important parameters in the model is the number of drawings to design for each of the five specialties which is set to 150 drawings for each specialty. No other literature reviewed includes this factor.

4. the effect of schedule pressure on quality in design;
the willingness to meet the target dates, especially when a project is late, has the consequence to increase the schedule pressure; this increases the productivity unless it is recognized impossible to meet the target date [27], but at the same time,

this decreases the design quality [31]. In the model, the quality of design goes down only when the ratio of calibrated progress to perceived progress is greater than one. This factor could vary from the value 1 to the value 0.9; so, the quality multiplier for the schedule pressure effect is assumed to have the minimum value 0.9 because even if the design is behind schedule, the designer work will not necessarily have a lower quality (see figure 19).

In this model, the way to take into account the schedule pressure in design is not as it is presented in the Tarek's model; it is a function of the perceived progress and of a calibrated progress already defined by the modeler in relation with the type of design; a calibrated progress is the expected progress of design at a specific time. If the perceived progress is lower than the calibrated progress, there is a pressure that will increase as the progress goes up. In the model, a "switch" function in the equation for the schedule pressure sets the ratio to one when the design has not begun in this specialty.

A level computes also the average quality of design as the design progress goes up. The average quality of design, a new variable not included in other models, is helpful to evaluate the quality of the shop drawings prepared by the contractor which is a function of the quality of the engineering design. If the accumulation of the quality of design that flows into the level each week is divided by the passed time, the average quality of design at that time is obtained. To prevent an error in the computation of the average quality of design, a "switch" function allows the quality of design to be accumulated in the level only if the design is in progress; also, this variable is set to zero when the perceived progress equals 1. In this last case, the model used the schedule completion date minus the start time for the total work-time spent to compute the average quality of design.

5.6.1.2 Progress of Design

The model considers the production of two types of drawings:

1. Drawings not needing rework [25]
2. Undiscovered drawings needing rework [25] but unknown at this time of simulation but they will be detected later.

All this process is in relation with the quality of design and the apparent progress [25]. The apparent production of drawings during each period of time in a simulation takes into account the number of designers and the apparent productivity. The apparent progress includes the drawings really completed that could be revised later due to work added or design changes, and drawings not really completed due to undiscovered errors that will be discovered as the design progress goes up. The time to detect rework goes down as the design progress goes up [25] (see figure 20).

The model divides the design added in two groups:

1. the drawings added affecting the drawings not needing rework;
2. the drawings added not affecting the drawings done.

The model assumes that the number of good drawings that must be reworked due to work added is equal to a percentage of the number of drawings added; the percentage of work added affecting the design is assumed to go up from 0% to 25% as the progress goes up (see figure 21).

Design changes is introduced with a "pulse" function which sets the first change occurrence and the interval of time between the changes. These changes simulate, for instance, the issuance of change orders requested by a consultant, the owner, the contractor or other parties. The "pulse" function is applicable for each specialty.

The cumulative real progress considers only the drawings not needing rework (good design) but some good design could be revised due to work added or due to design changes as requested by the consultants, the owner or the developer.

The fraction perceived complete of design is the ratio of the cumulative perceived progress to the sum of these variables: the initial number of drawings, the total design work added, the cumulative undiscovered drawings to rework, the cumulative drawings to rework due to the design added and the cumulative drawings to revise due to design change. In the Richardson's model, the fraction perceived completed is the ratio of the cumulative perceived progress to the initial quantity of tasks; no other factor was detailed and the simulation runs until the real progress is one hundred percent complete, meaning that the total number of good drawings completed is equal to the initial number of drawings. In this study, the end of the simulation is a function of the fraction perceived completed.

Usually, the cumulative perceived progress has an "S" curve shape. In other words, at the beginning, the design progress increases less rapidly (see figure 22).

The model computes for each step of the simulation a calibrated progress that varies in function of the time already spent in the design; knowing the passed time, the ratio (passed time/ total expected design time) can be computed for each specialty and then, an anticipated progress is defined for that specific timestep. In the equation for the time spent in design, a "clip" function selects the value 1 when the design is perceived completed in order to set the calibrated progress to 1; a "switch" function sets the ratio value to 1 if the design is not started.

To evaluate the elapsed time from the beginning of the design for each specialty, it is esssential to estimate the start date of each specialty. Excepted for the first specialty, the civil specialty, the model itself determines the start time date of each specialty, a process to catch the time when the work of each specialty start must be defined. Each start date will be included in a level at the appropriate time, and knowing that the rate is calculated at the previous time (time.kl), it is possible to select only the start time for each specialty. The model uses a "flag" to identify an action because it is not easy to keep the start date of each specialty in using the system dynamics theory: when the "flag" rate has the value 1, the present time (time.k) is selected. This "flag" rate has the value 1 only when the design phase starts and when the level of "flag" is equal (or greater) to 1; this will happen one step after the start date according to the system dynamics theory: a level represents a delay 1. No other model presents similar equations for this subject.

5.6.1.3 Productivity in Design

The model not only takes into account the apparent productivity but also the perceived productivity, the indicated productivity and the real productivity [25]: the apparent productivity in design is one of the most important factors in the design process; it is set at 0.208

drawing/designer/week [3] but this gross productivity factor is affected by these factors:

1. the schedule pressure effect [31]:

   the schedule pressure effect on design productivity is affected by the perceived progress and the calibrated progress which is an expected progress according to the elapsed time, as already described; if the calibrated progress is under the perceived progress, this productivity multiplier could decrease until the value 0.90 because the "designers will tend to decrease the productivity to stay on the known target date. If the calibrated progress is greater than the perceived progress, the designers will try to stay on the target date and, therefore, will increase the productivity until a point where the designers perceive that there is no possibility to meet the target" [27]; it is assumed that in that case, the productivity will increase up to 20% to stay on the target date and the schedule pressure factor could decrease up to 0.80 if the designers feel that there is no possibility to meet the target (see figure 23).

In the model, the manager could modify the willingness to recognize the schedule pressure effect if it is recognized that the design is behind schedule: normally, the willingness goes up as the time remaining goes down because the probability to meet the target date decreases as the time remaining goes down.

2. the job size effect:
the productivity multiplier for the effect of job size will decrease the productivity in a large project on account of the number of designers to coordinate and a slow down in the decision process. "A project with more than about 250 000 man-hours will have a smooth declining in the productivity of about 1% for each 100 000 man-hours. A small project under 250 000 man-hours will have a higher productivity" [3] (see figure 24).

3. the learning effect:
"the learning effect multiplier implicates that the design becomes repetitive. The learning effect augments the apparent productivity up to the resource run-down of each discipline when there is less production possible due to a lack of similar work" [10].

With time, the designers learn to do their job with a greater productivity, especially if their jobs are more complexed. Normally in an industry, the learning effect factor is described with a percentage factor, i.e., a 90% learning effect factor which means that if the production doubles, the learning factor increases by 10%; for instance, if a job is 50% completed with a learning effect factor of 1.07, then a job 100% complete means that the learning effect factor at this time is 1.18, i.e., 1.07 times 1.1. In this model, a non-linear variable presents the learning factors that vary from 0.93 to 1.09 with major variations in the first part of the design, but another variable, playing a role when the progress is greater than 70%, reduces the learning effect factor because the designers are now more involved with specific details (see figure 25).

4. the productivity multiplier is in relation with the indicated workforce needed in taking into account of the relations between the specialties (see figure 26).

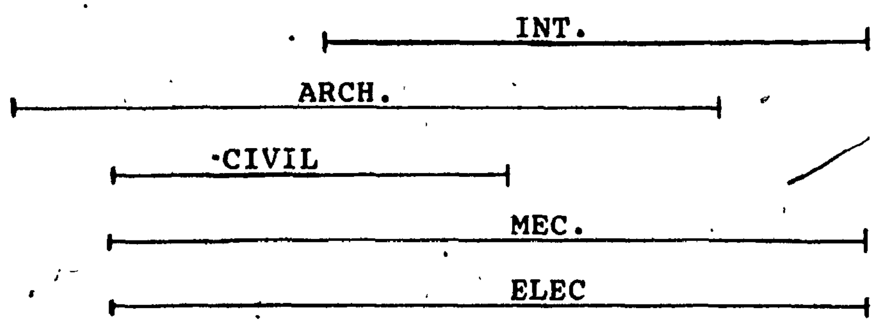


figure 26. Bar chart of activities sequences in design

This multiplier factor has the value "0" or "1"; this factor has the value "1" if all the following criteria are true for the respective specialties, otherwise, it has the value "0":

1. for the civil design:
   - if the architectural design progress is greater or equal to 50%
   - if the civil design progress is greater or equal to 85%, the civil design can go ahead in the design process if the mechanical design is at least 30% complete
   - if the civil design progress is greater or equal to 85%, the civil design can go ahead in the design process if the electrical design is at least 20% complete

2. for the mechanical design:
   - if the architectural design progress is

greater or equal to 50%

- if the mechanical design progress is greater or equal to 60%, the mechanical design can go ahead in the design process if the progress gap between the electrical design and the mechanical design is at least -50%. In other words, if the mechanical progress is 50%, the mechanical designers want electrical drawings to go ahead in their mechanical design
- if the mechanical design progress is greater or equal to 85%, the mechanical design can go ahead in the design process if the difference between the mechanical design progress and the interior design progress is greater than 60%; then, the mechanical design progress can be complete

3. for the electrical design:
   - if the architectural design progress is greater or equal to 5%
   - if the electrical design progress is greater or equal to 85%, the mechanical design can go ahead in the design process if the progress gap between the interior and the electrical design is at least -85% (not more

than 15%). In other words, if the electrical progress is 90%, the interior design must be at least 5% completed

- if the electrical design progress is greater or equal to 60%, the electrical design can go ahead in the design process if the gap between the mechanical design progress and architectural design progress are at least -30% completed to allow the electrical to continue the design

The architectural design has no constraint to start this design.

4. for the architectural (exterior)design:
   - if the architectural design progress is greater or equal to 40%, the difference between the civil progress and the architectural design is at least -40%; so, the architectural designers need continually to receive information of civil designers when the architectural progress reaches 40%
   - if the architectural design progress is greater or equal to 85%, the architectural design can go ahead in the design process if

the mechanical design progress is at least greater to 40% to complete the architectural design

- if the architectural design progress is greater or equal to 85%, the architectural design can go ahead in the design process if the electrical design progress is at least greater to 50% to complete the architectural design

5. for the interior design:
   - if the architectural design progress is greater or equal to 60%
   - if the mechanical design progress is greater or equal to 30%
   - if the electrical design progress is greater or equal to 30%.

Except for the schedule pressure factor, these factors were not included in relevant literature. Also, the equation defining the schedule pressure factor is not exactly the same as described in the Tarek's model: in this model, it is related to a calibrated progress versus a perceived progress, rather than an indicated completion date versus a schedule completion date or the effort done at that time versus the effort planned to be spent at that time.

"The perceived productivity in design changes smoothly in function of the indicated productivity and the time to perceived productivity" [25] which is assumed to be 4 weeks; the indicated productivity is a ponderation of a real productivity and of gross productivity considering the willingness of the manager to take the real productivity. This willingness is a function of the fraction perceived complete of design: if the perceived progress goes up, the willingness to take consideration of the real productivity or the drawings really good goes up (see figure 27).

During a simulation, the real productivity is computed in dividing the quantity of good drawings that are produced to the total number of designers for each timestep. A level for the drawings not needing to be reworked includes only the drawings not needing rework that are designed at each timestep of the simulation: a variable substracts the cumulative number of good drawings produced at the previous time (time.k-DT) to the rate of good drawings done this period.

To prevent an interruption in computing the real productivity when the workforce becomes zero at the end of their design, the total number of good drawings produced is divided by the cumulative workforce days. To know the cumulative number of man-days in design, the total design workforce is multiplied by the number of workable days per week which is set to five days in the model.

5.6.1.4 The Effort Perceived Remaining in Design

To evaluate the effort remaining (persons-weeks), the number of drawings remaining is divided by the perceived productivity; the number of drawings remaining is evaluated in taking into account the initial number of drawings, the design added, the undiscovered drawings to rework, the design to rework due to design change, the design to rework due to design added and the cumulative perceived quantity of drawings complete.

5.6.1.5 The Workkforce in Design

If the design effort perceived remaining is divided by the time remaining, the indicated workforce is identified but, in this case, the workforce distribution is a rectangular one. A multiplier factor is introduced in this model to have a trapezoidal distribution, a factor not included in other system dynamics models studied.

Suppose that for the project, detailed estimates add up to 10 000 man-hours and it is assumed that 2000 man-hours is roughly equal to one man-year, a rapid division shows that five man-years must be spent in order to complete the project design; but this is not the right method to use in the manpower planning in a project because the distribution is not a trapezoidal distribution, as it is usually. "In fact, the maximum level of resources appears to be around 1.6 times greater than the average number of designers required" [3]; in this model, a complete build-up and a run-down of the design resources are assumed when the progress reaches 22% and 40% respectively [3] (see figure 28).

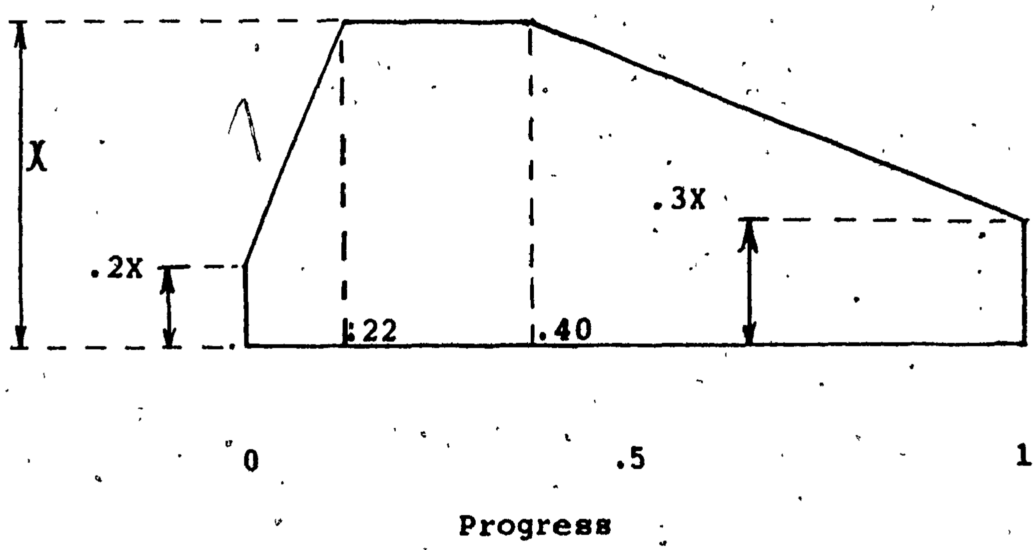


Figure 28. Trapezoidal distribution of designers [3]

The determination of the trapezoidal factors requires first of all, the presentation of a detailed rectangular distribution: for instance, if the effort perceived remaining is 69,5 persons-weeks and if the duration is 10 weeks, the number of men required is 6,95 (or 7) from the beginning to the end of the project (see table 1),

PROGRESS %	EFFORT PERCEIVED REMAINING (person-week)	DURATION (week)	NUMBER OF MEN (person)
0	69,50	10	6,95
	- 6,95		
10	62,55	9	6,95
	- 6,95		
20	55.60	8	6,95
	- 6.95		
30	48,65	7	6,95
	- 6,95		
40	41,70	6	6,95
	- 6,95		
50	34,75	5	6,95
	- 6,95		
60	27.80	4	6,95
	- 6,95		
70	20,85	3	6,95
	- 6,95		
80	13,90	2	6,95
	- 6,95		
90	6,95	1	6,95
	- 6,95		
100	0,00	0	6,95

Table 1. Computation for a rectangular distribution of designers

The trapezoidal factors must take into account these two parameters:

1. the required number of men using the trapezoidal distribution compared to the constant number of men using the rectangular distribution
2. the effort perceived remaining using the trapezoidal distribution compared to the effort perceived remaining using the rectangular distribution.

Also, the trapezoidal factors vary in relation with the fraction perceived completed of design. Various factors could be used for another workforce distribution (see table 2).

PROGRESS %	EFFORT PERCEIVED REMAINING (person-week)	DURATION REMAINING (week)	TRAPEZOIDAL FACTOR
0	69,50	$\frac{0,29*69,5}{2}$=10	$\frac{2/6,95}{69,5/69,5}$ =0,29
10	69,5-($\frac{2+5,7}{2}$) =65,7	$\frac{0,78*65,7}{5,7}$ =9	$\frac{5,7/6,95}{65,7/62,55}$ =0,78
20	65,5-(5,7+9,6)=58,20	$\frac{1,32*58,20}{9,6}$=8	$\frac{9,6/6,95}{58,20/55,6}$ =1,32
30	58,20-((9,6+10)/2)*,2 -(10*.8) =48,25	$\frac{1,45*48,25}{10,0}$=7	$\frac{10/6,95}{48,25/48,65}$ =1,45
40	48,25-((10*1) =38,25	$\frac{1,52*38,25}{9,7}$=6	$\frac{9,7/6,95}{38,25/41,7}$ =1,52
50	38,35-((8,6+9,7)/2) =29,20	$\frac{1,47*29,2}{8,6}$ =5	$\frac{8,6/6,95}{29,20/34,75}$ =1,47
60	29,20-((7,5+8,6)/2) =21,18	$\frac{1,42*21,18}{7,5}$=4	$\frac{7,5/6,95}{21,18/27,80}$ =1,42
70	21,18-((7,5+6,5)/2) =14,18	$\frac{1,37*14,18}{6,5}$=3	$\frac{6,5/6,95}{14,18/20,85}$ =1,37
80	14,18-((6,5+5,2)/2) = 8,33	$\frac{1,24*8,33}{5,2}$ =2	$\frac{5,2/6,95}{8,13/13,9}$ =1,24
90	8,33-((5,2+4,1)/2) = 3,68	$\frac{1,11*3,68}{4,1}$ =1	$\frac{4,1/6,95}{3,68/6,95}$ =1,11
100	3,68-((4,1+3,1)/2) = 0,08	$\frac{0,48*0,08}{3,1}$=,01	$\frac{3,0/6,95}{0,08/0.08}$ =0,48

Table 2. Computation for the trapezoidal distribution of designers

The table 3 indicates the corresponding number of resources for the trapezoidal distribution of designers to prove that these trapezoidal factors are related to the desired trapezoidal distribution (see figure 29).

progress	effort perceived remaining*factor / duration remaining	=resources
%	(PERSON)	(PERSON)
0	69,50*0,29/10=	2
10	65,70*0,78/ 9=	5,7
20	58,20*1,32/ 8=	9,6
30	48,25*1,45/ 7=	10,0
40	38,25*1,52/ 6=	9,7
50	29,20*1,47/ 5=	8,6
60	21,18*1,42/ 4=	7,5
70	14,18*1,37/ 3=	6,5
80	8,33*1,24/ 2=	5,2
90	3,68*1,11/ 1=	4,1
100	0,08*0,48/.01=	3

Table 3. Resources distribution

As explained in the Richardson's model, the number of designers needed is an equilibrium between the indicated number of designers and the actual total number of designers. The desired equilibrium could change during the design process; for instance, at a certain stage, the management could desire to stay with the total actual number of designers. The model simulates the willingness (between the value "0" and "1") of the manager to change the workforce in relation with the perceived progress of design. If the willingness is equal to "1", the manager wants the indicated workforce which is also in relation with a trapezoidal distribution of designers; if the willingness is "0", the manager is not willing to hire other designers. In this model, the management is willing to have the indicated workforce calculated with the trapezoidal distribution of designers (see figure 30). As explained before, the trapezoidal distribution was not in the Richardson's model or other models. Also, the indicated workforce value does not take into account potential interferences between the specialties, these interferences are considered in the apparent productivity definition.

Another factor not described in systems dynamics literature that could influence the number of designers needed is a ceiling on the number of designers. The manager can set a ceiling on the total number of designers to better represent the reality. The model chooses the number of designers sought between the computed number of designers needed or the designers ceiling which could be modified as the perceived progress goes up. In the base model, the ceiling is fixed to 2 000 designers during all the process; this number of designers will result in no ceiling effect on the number of designers if it is not a mega-project (see figure 31). In other simulations, the ceiling is reduced to a number lower than the workforce needed, then the model takes the ceiling value, no new designer is hired, and the ratio workforce with experience to the new workforce goes up.

Knowing the gap between the workforce sought and the actual total design workforce which is composed by the designers with experience and the new designers, the management can hire or transfer designers. If the gap is negative, no designer is hired.

In the model, the hiring delay and the assimilation delay are asssumed to 3 and 6 weeks respectively which appears to be reasonable; the level of new designers on the project is composed by the rate of designers hired minus these factors:

1. the rate of new designers that become assimilated after a delay
2. the rate of new designers that are transferred because, at a specific time, less designers are needed on the project.

In this model, it is asssumed that, at the beginning, the number of designers is only composed of architectural designers with experience and is set to 20% of the peak value of the trapezoidal distribution.

So, the initial number of architectural designers is set to:

$$\frac{0.28 * \text{initial number of drawings}}{\text{gross productivity} * \text{initial schedule completion date}}$$

This formula is derived from the following computation in taking into account the total perceived man-weeks distributed trapezoidally as it is in figure 28:

1. the area to the left: (.20X+X)*.22*SCDND/2
2. the area of the rectangle: (.40-.22)*SCDND*X
3. the area to the right: (1-.40)*SCDND*(.3X+X)/2

then,

(.13*SCDND*X)+(.18*SCDND*X)+(.39*SCDND*X) = TOTPMW

then, .70*SCDND*X = TOTPMW

then, $X = \frac{\text{TOTPMW}}{.70*\text{SCDND}}$

where SCDND = initial schedule completion date
TOTPMW= total perceived quantity of man-weeks
X = peak number of designers

Initially, the total perceived quantity of man-weeks or the total perceived effort required is a function of the initial quantity of drawings and the assumed productivity. If the perceived effort required is converted in man-days in taking five man-days per week, if the initial schedule completion date is converted in days and if the initial number of designers is set to 20% of the peak value, the equation to evaluate the number of architectural designers that are initially on the project is:

$$= \frac{0.2*IW/(GPRODD/5)}{SCDND*5*.70} \quad \frac{(draw./draw./person\text{-}week/days/week)}{(week*days/week)}$$

$$= \frac{0.2*IW/GPRODD}{SCDND*.71} \quad person$$

$$= \frac{0.28 * IW}{GPRODD*SCDND} \quad person$$

where IW = initial number of drawings
GPRODD = gross productivity in design

The new designers become designers with experience after an assimilation period; the rate of designers that become experienced is computed from the assimilation rate of designers which is also reduced by these factors:

1. the rate of experienced designers that are transferred or fired when the workforce sought is less than the actual total workforce
2. the rate of designers that quit the project for other projects. The average employment time of designers is assumed to seventy weeks.

As described in the Tarek's model, a variable identifies the number of designers to be fired or transferred and designers with experience are transferred only if there is no new designer on the project; a "minimum" function insures that the number of new designers transferred can not be greater than the actual number of new workforce and another "minimum" function insures that the number of designers with experience that are transferred, is not greater than the number of designers with experience. If the project requires more workers, i.e., the workforce gap is greater than zero, the transfer rate is set to zero with the "maximum" function. In the model, the transfer delay is set to two workable weeks [31].

If the cumulative workforce-days is added to the effort perceived remaining in design, the total perceived workforce-days for each specialty is measured; five working days per week are assumed in this model.

5.6.1.6 The Indicated Completion Date in Design

In each simulation step, the indicated completion date is estimated in adding the time perceived required to complete the design to the schedule completion date. If the design is not in progress, the initial schedule completion date is selected. Also, the indicated completion date must not change when this design phase will be completed; the equation takes the value of the schedule completion date in design.

5.6.1.7 The Time Perceived Required to Complete the Design

The effort perceived remaining divided by the number of designers sought indicates the time perceived required to complete the design [25]. A "switch" function is used to prevent a division by zero when the workforce sought of a specialty equals zero. This ratio is multiplied by a required trapezoidal factor to be stuck on the right time because the designer's distribution is not rectangular but it is trapezoidal.

Because the model takes into account five specialties, each specialty needs a specific equation to evaluate the time perceived required to complete a specialty when the specialty is in progress:

1. for the civil design, the time perceived required to complete this design is the longest time between these two times:
   - the time perceived required to complete the civil design
   - forty percent of the time to complete the architectural design. The assumption here is that the design of civil work can not be

completed before it has expired 40% of time perceived required for architectural design

2. for the mechanical design, the time perceived required to complete this design is the longest time between these times:

- the time perceived required to complete the mechanical design
- 70% of the time perceived required to complete the electrical design
- 70% of the time perceived required to complete the interior design

3. for the electrical design, the time perceived required to complete this design is the longest time between these times:

- the time perceived required to complete the electrical design;
- 70% of the time perceived required to complete the mechanical design;
- 70% of the time perceived required to complete the interior design.

4. for the architectural design, the time perceived required to complete this design is the longest time between these times:

- the time perceived required to complete the architectural design;
- 60% of the time perceived required to complete the civil design;
- when the mechanical design is completed to 60%;
- 60% of the time perceived required to complete the electrical design.

5. for the interior design, the time perceived required to complete this design is the longest time between these times:
   - the time perceived required to complete the interior design;
   - 80% of the time perceived required to complete the mechanical design;
   - 80% of the time perceived required to complete the electrical design.

So, because each specialty has specific characteristics, this generates an equation for each specialty in accordance with the dynamo language.

These percentages assumed are reasonable values based on the construction of an office building.

5.6.1.8 The Time Remaining in Design

The time remaining to complete the design is computed in taking the schedule completion date minus the present time in the simulation [25]. In this equation, the "switch" function sets the time remaining to the duration of each specialty before they start their design phase; a clip function is used to set the time remaining to zero when the design is completed and a maximum function is used to prevent a division by zero when the model starts the simulation run, i.e., "time.k" equals zero.

5.6.1.9 Schedule Completion Date for Each Specialty in Design

In this model, reasonable values are assumed in the model to set an initial schedule completion date for each specialty in design; an equation is necessary for each specialty because the durations, criteria and interrelations of one specialty with the other specialties are not the same:

1. for the civil design:
   - an expected duration
   - this specialty will start when the expected

duration for the architectural design is 10% complete

2. for the mechanical design:
   - an the expected duration
   - this specialty will start when the architectural design is 20% complete

3. for the electrical design:
   - an expected duration
   - this specialty will start when the expected duration for the architectural design is 25% complete

4. for the (exterior) architectural design:
   - the design starts in considering the architectural process; so, only the duration of the architectural design is needed to know the initial schedule completion date of this specialty.

5. for the interior (architectural) work:
   - an expected duration
   - this specialty will start when the expected duration to design the architecture is 30% complete.

In the design process, the schedule completion date is represented by a level that varies in relation with the net addition to design schedule [25]. The gap between the indicated completion date and the schedule completion date will be adjusted accordingly with the schedule adjustment time [25]. The schedule adjustment time is assumed to decrease from 20 weeks to 4 weeks in relation with the perceived progress of design because at the beginning of the design phase, the manager is not willing to modify the schedule and as the progress of work goes up, the manager has a better understanding of the real progress and he becomes more willing to change the schedule if it is necessary; at the end, the manager has no choice if the designer is not able to meet the target date, the schedule must be postponed (see figure 32).

5.6.2 Construction Subsystem

As described before, the construction subsystem is similar to the design subsystem even if many non-linear variables have a different shape, but there are more variables added in this subsystem to better define the interrelations within the construction specialties and the design specialties.

5.6.2.1 Construction Quality

The construction quality is a smooth function with a quality delay set in the model to five weeks for each specialty. Essentially the construction quality is not only a constant but a variable that changes with the perceived construction progress: at the beginning, every worker wants to do a perfect job, but his motivation decreases with time; in the second phase of the project, the manager requires more efforts from workers for them to be on schedule and at the end of the project, the motivation decreases due to the stress of seeking a new job or to be placed on another unknown project [27]. In the model, the construction quality can not be equal to 100% and a value of 99% is assumed at the beginning of the construction process; until 60% progress, the quality goes down to 93%; then, up to 80% progress, the quality goes up to 96%; at the end, the quality factor goes down to 92% ; these values are not exact values but in system dynamics, realistic values are acceptable to analyse the behavior modes and to compare with other policies (see figure 33).

Also, the quality of construction is affected by these parameters:

1. the effect of the construction experienced workforce on quality;
   the construction quality is affected by the experience of the workforce to the current project; the more workforce with experience there is in regard to new workforce, the greater is the factor for the construction quality [31]. As the number of experienced workforce goes up, the effect on quality goes up. This minimum quality multiplier is set to 75% even if only new workforce could be on site; the maximum factor is set to 98% (see figure 34)

2. the effect of schedule pressure on the construction quality [31];
   the construction could be affected by the schedule

pressure; the construction quality goes down only when the ratio of the "calibrated" progress to the perceived progress is greater than one. The schedule pressure effect varies between the value 1 and 0.90 when the ratio goes from 0 to 2.5; the effect factor always has the value 1 for a ratio lesser or equal to 1 (see figure 35).

The ratio $\frac{\text{"elapsed time}}{\text{total expected time}}$" for each specialty is needed to compute the percentage of elapsed time in order to estimate the cumulative calibrated progress which is lower than the time progress: for instance, in the model, a 40% time progress indicates a 33% calibrated progess of the construction (see figure 36). Because the time changes in a simulation, a "clip" function selects the value one (1) when the work is perceived completed in order to set the calibrated progress to one (1); also, a "switch" function sets the ratio value to one (1) if there is no progress in the respective specialty. The calibrated progress definition was not in other system dynamics literature.

In the model, simulations can also be done with a non-linear willingness to recognize the schedule pressure effect; the willingness goes up as the progress goes up (see figure 37).

Because the modeler gives only the start date of the civil work, the first specialty required on the site first of all and because there is evolution of the time during a simulation, specific equations have been developed to catch up the start dates of the other specialties in order to know the elapsed construction time; so, with the system dynamics theory indicating that a level simulates a delay (in fact, a delay 1), it is possible to select and keep the other four construction start dates: for each step during a simulation, the time inflows in a "level" and the previous time outflows of the "level", keeping in this "level" only one date; when a construction phase starts, the start time is selected and no other date is included in this "level".

3. the effect of delivery of material on the construction quality;
this quality multiplier takes into account the effect of a lack of material on the construction quality. In the model, if the ratio of material on site to the material needed is lower than one, the quality is affected by a multiplier factor that

could goes down up to .85. The material needed on site is in relation with the perceived construction progress. The construction productivity is also affected if there a lack of material (see figure 38).

4. the effect of work added due to design added or changed on construction quality;
it is a new input compared to the relevant literature; the more rework, the greater the ratio, the lesser the motivation, but it is also reasonnable to take into account that the motivation could not decrease until the value "zero". A quality multiplier that takes into account the motivation of workers due to effect of work added, goes down to 0.96 when the ratio of the revised drawings after the construction start to the total number of drawings, goes up (see figure 39).

5.6.3.2 Construction Progress and Productivity

The model considers the production of two types of construction work:

1. Construction not needing rework (the real good work) [25]

2. Undiscovered construction work needing rework (that will be identified after a delay) [25].

All this process is in relation with the quality of construction work and the apparent progress which is in relation with the workforce and the apparent productivity [25].

The sum of these two types of construction work is the perceived construction progress. So, knowing the perceived progress and the total number of work to realize, the fraction perceived completed of the construction is identified [25].

The workers produce good and bad work at each period of time during the construction, but they don't know exactly if their work is completely well done; the time to detect these errors goes down as the progress goes up. The time to detect rework equals to 4 weeks, meaning that the procedure to advise the contractor for the rework takes about four weeks (see figure 40). The effect is a lower increase of the cumulative perceived progress.

The cumulative real progress takes into account not only the construction jobs not needing rework (good work), according to the apparent progress and the quality of the construction, but also good work that must be revised due to work added, design changes or design errors after the construction start; a "clip" function checks to not deduct to the cumulative construction work not needing to be rework, a greater quantity of construction work than the actual cumulative work not needing to rework; a "switch" function opens the valve for the outflow of construction good work to be revised when the actual time is equal or greater to the construction start time fixed by the modeler.

It is recognized that the construction man-hours budget is about six times greater than the design man-hours budget [3]. So, in this model, the construction gross productivity is assumed to be the same value than the design gross productivity but a constant generates construction jobs equivalent to six times the number of drawings.

The efforts perceived remaining is the ratio of the construction work remaining to the construction perceived productivity (workers-week) [25]. A "switch" function selects the construction perceived productivity only when the construction is in progress. The construction perceived productivity changes smoothly in relation with the indicated productivity and the time to perceive the productivity which is set to 6 weeks.

The indicated productivity is an equilibrium between the real productivity or the gross productivity [25]; in the model, the manager is more willing to take into account the real productivity as the fraction perceived complete goes up (see figure 41).

The real productivity is computed in taking the quantity of good construction jobs done, divided by the total effort used in the period. The total number of good jobs produced divided by the cumulative workforce-days is applied at the end of the construction of each specialty to prevent an interruption of computing (the workforce level has the value "0").

The total perceived construction work is the sum of theses parameters:

1. the initial number of drawings converted in construction jobs
2. the number of drawings added converted in construction jobs

3. the undiscovered construction work to rework
4. the construction to rework due to the revised drawings after the construction start.

5.6.2.3 TIme Perceived Required to Complete the Construction

The time perceived required to complete a construction project is a function of the construction effort perceived remaining and the sought workforce [25]. A "switch" function takes the work duration of each specialty if the construction has not begun in order to prevent a division by the value "0".

5.6.2.4 The Trapezoidal Distribution of Workers

Also, because a trapezoidal workforce distribution is required even if it was not described in system dynamics literature, trapezoidal factors must be introduced in the equation to stick to the right time as the progress increased. These factors are also used in the equation for the indicated construction workforce. The trapezoidal factors are calculated in taking into account these two variables:

1. the required number of workers using the

trapezoidal distribution compared to the constant number of workers using the rectangular distribution;

2. the effort perceived remaining using the trapezoidal distribution compared to the effort perceived remaining using the rectangular distribution.

The table 4 shows that the number of workers required for a rectangular distribution is six according to the effort perceived remaining assumed at the beginning of the construction to 62.2 workers-weeks and according to the work duration set to 10 weeks:

PROGRESS %	EFFORT PERCEIVED REMAINING (workers-weeks)	DURATION (week)	NUMBER OF WORKERS (workers)
0	62,2	10	6,2
	- 6,2		
10	55,8	9	6,2
	- 6,2		
20	49,6	8	6,2
	- 6.2		
30	43,4	7	6,2
	- 6,2		
40	37,2	6	6,2
	- 6,2		
50	31,0	5	6,2
	- 6,2		
60	24,8	4	6,2
	- 6,2		
70	18,6	3	6,2
	- 6,2		
80	12,4	2	6,2
	- 6,2		
90	6,2	1	6,2
	- 6,2		
100	0,0	0	6,2

Table 4. Computation for the rectangular distribution of workers

The table 5 indicates the factors for a trapezoidal distribution with a worker's peak set between 40% and 70% of construction progress based on the analysis done on a major construction project complete:

PROGRESS %	EFFORT PERCEIVED REMAINING (workers-weeks)	DURATION REMAINING (week)	TRAPEZOIDAL FACTOR
0	68,5	$\frac{0{,}15*68{,}5}{1}=10$	$\frac{1/6{,}85}{68{,}5/68{,}5}=0{,}15$
10	$68{,}5-\left(\frac{3{,}3+1}{2}\right)=66{,}4$	$\frac{0{,}45*66{,}4}{3{,}3}=9$	$\frac{3{,}3/6{,}85}{66{,}4/61{,}7}=0{,}45$
20	$66{,}4-\left(\frac{3{,}3+5{,}5}{2}\right)=62{,}0$	$\frac{0{,}71*62{,}0}{5{,}5}=8$	$\frac{5{,}5/6{,}85}{62{,}0/54{,}8}=0{,}71$
30	$62{,}0-\left(\frac{5{,}5+7{,}7}{2}\right)=55{,}4$	$\frac{0{,}97*55{,}4}{7{,}7}=7$	$\frac{7{,}7/6{,}85}{55{,}4/48{,}0}=0{,}97$
40	$55{,}4-\left(\frac{7{,}7+10{,}}{2}\right)=46{,}5$	$\frac{1{,}29*46{,}5}{10{,}}=6$	$\frac{10{,}0/6{,}9}{46{,}5/41{,}1}=1{,}29$
50	$46{,}5-(10{,}*1)=36{,}5$	$\frac{1{,}37*36{,}5}{10{,}}=5$	$\frac{10{,}0/6{,}9}{36{,}5/34{,}3}=1{,}37$
60	$36{,}5-(10{,}*1)=26{,}5$	$\frac{1{,}51*26{,}5}{10{,}}=4$	$\frac{10{,}0/6{,}9}{26{,}5/27{,}4}=1{,}51$
70	$26{,}5-(10{,}*1)=16{,}5$	$\frac{1{,}82*16{,}5}{10{,}}=3$	$\frac{10{,}0/6{,}9}{16{,}5/20{,}6}=1{,}82$
80	$16{,}5-\left(\frac{10{,}+6{,}8}{2}\right)=8{,}1$	$\frac{1{,}68*8{,}1}{6{,}8}=2$	$\frac{6{,}8/6{,}9}{8{,}1/13{,}7}=1{,}68$
90	$8{,}1-\left(\frac{6{,}8+4{,}2}{2}\right)=2{,}6$	$\frac{1{,}56*2{,}6}{4{,}2}=1$	$\frac{4{,}2/6{,}9}{2{,}7/6{,}9}=1{,}56$
100	0	0	=1

Table 5. Computation for the trapezoidal distribution of workers

Using these factors, the corresponding numbers of workers trapezoidally distributed are defined to demonstrate that these factors are accurate (see table 6 and figure 42):

PROGRESS	effort perceived remaining * factor / duration remaining	= NUMBER OF persons
(%)	(workers)	(workers)
0	68,5*0,15/10=	1,
10	66,4*0,45/ 9=	3,3
20	62,0*0,71/ 8=	5,5
30	55,4*0,97/ 7=	7,7
40	46,5*1,29/ 6=	10,0
50	36,5*1,37/ 5=	10,0
60	26,5*1,51/ 4=	10,0
70	16,5*1,82/ 3=	10,0
80	8,1*1,68/ 2=	6,8
90	2,6*1,56/ 1=	4,2
100		0,

Table 6. Worker's distribution

5.6.2.5 The Indicated Completion Date in Construction and the Time Perceived Required to Complete the Construction

For each period of time during a simulation, the model identifies the indicated construction completion date. The indicated completion date is defined as being, the time perceived required to complete the work added to the actual time [25]. But because there are only five specialties related between them, the time perceived required to complete a specialty is not only in regard with the specialty itself, but may be in relation with other specialties; in the model, specific equations define these relations to demonstrate the capabilities of the system dynamics theory:

1. for the civil work, the time perceived required is searched for the civil work only
2. for the mechanical work, the maximum time perceived required is searched between the civil, mechanical, electrical, architectural work and 90% of the time perceived required to complete the interior work
3. for the electrical work, the maximum time perceived required to complete the mechanical work
4. for the architectural work, the maximum time perceived required is searched between the civil and architectural work
5. for the interior work, the maximum time perceived required is searched between the civil, electrical, architectural work and 90% of the maximum time perceived required to complete the mechanical or the interior work

Additionnal possibilities are included in the determination of the indicated construction completion date: with the "switch" functions, the modeler can select either of these cases to take into account:

1. the postponement of the construction schedule completion date before the construction begins if there is a postponement of the design schedule

completion date in order to keep the same duration between the design schedule completion date and the construction schedule completion date expected initially (see figure 43)

2. before the construction starts, the model takes into account the maximum time between the construction schedule completion date expected initially and the schedule completion date in design in order to prevent that the design completion date is greater than the construction completion date; the base model is set to this value (see figure 44).

<u>Taking into account of slippage in the design phase</u>

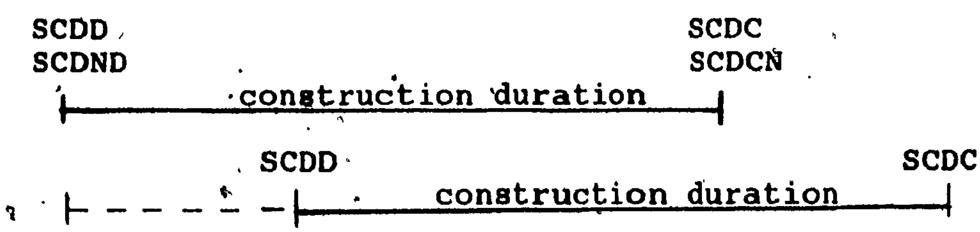


figure 43. The indicated completion date modified by the design schedule completion date

Not taking into account of slippage in the design phase

```
SCDD                                              SCDC
SCDND                                             SCDCN
|--------------- construction duration ---------------|

                SCDD                              SCDC
|- - "A" - - -|------- construction duration -"A" ----|
```

figure 44. The indicated completion date not modified by the schedule completion date in design

5.6.2.6 The Schedule Completion Date in Construction

From the gap between the indicated completion date and the schedule completion date, the construction schedule completion date is adjusted continuously in taking into account the schedule adjustment time [25]. The construction schedule adjustment time goes down from 20 weeks to 3 weeks in relation with the perceived progress of construction; the manager is more willing to modify the schedule as the progress of work goes up; he has a better perception of the real progress, and near the end, he has no other choice than to modify the schedule if the project can not be finished at the stipulated target date (see figure 45).

Initially, the schedule completion date of a specialty is set in relation with the overall construction start time, with the progress of other specialties, and with the stipulated duration of each specialty which is set to 40 weeks in the base model:

1. the initial schedule completion date of civil work is set taking into account the duration of civil work and the construction start date of the civil work
2. the initial schedule completion date of the mechanical work is set in assuming that this construction starts when the expected civil work duration is 30% complete
3. the initial schedule completion date of electrical work is set in assuming that this construction starts when the expected civil work duration is 40% complete
4. the initial schedule completion date of architectural work is set in assuming that this construction starts when the expected civil work duration is 20% complete
5. the initial schedule completion date of interior work is set in assuming that this construction starts when the expected civil work duration is 50% complete.

If the construction of a specialty is in progress, the time remaining to complete the work is deducted in substracting the actual time in the simulation to the the schedule completion date; if the work is not under progress, the initial expected duration is the time remaining.

5.6.2.7 Construction Productivity

The apparent construction productivity is a variable affected by the gross productivity already defined and other variables:

1. the schedule pressure effect on productivity; if the perceived progress is ahead of the calibrated progress stipulated by the modeler, the productivity tends to decrease because the workers tend to stay on the known target date; if the perceived progress is lesser than the calibrated progress, the workers try to be on the target date and, therefore, the schedule pressure effect increases the productivity until a point where the workers perceive that there is no possibility to meet the target date [27] (see figure 46).

   In the model, the willingness to recognize the schedule pressure effect goes up as the progress goes up.

2. the learning effect on productivity;
   the learning curve theory is predicated upon the observed fact that the production time for a given type of work generally decreases with the number of repetitions of the task due to an improvement of the physical adaptation. If a contractor expects a 90 percent learning curve for the repetitive portions of a particular project, he would therefore achieve a ten percent savings in total labor over a no-learning situation if the work goes as planned.

In the model, the learning effect variable, a variable not described in system dynamics literature, is in relation with the fraction perceived completed of construction: at the beginning of the construction, the learning effect goes up rapidly. There is a lost of the learning effect due to the worker's vacations which have a negative effect every six months after the construction start, and due to work added; also the learning effect decreases smoothly when the progress is near the end due to the construction of more particular work instead of repetitive work [10] (see figure 47).

In the construction of a building, the learning curve is modified constantly because there are different learning curves due to the various specialties involved. Repetition of complex operations tends to exhibit high ratio of productivity improvement.

3. the area workload effect on productivity; if there are too many workers in an area, the productivity could decrease; in fact, it is demonstrated that under 160 square meters per person, the productivity will go down. This productivity multiplier is set to the minimum value of 85% when the area factor equals or is less than 80 square meters per worker; over 160 square meters per worker, there is no effect on the area workload [3] (see figure 48).

The area workload factor is identified in taking into account two assumptions:

3.1 if the construction work is in progress, the ratio of the floor area available to the total construction workforce, is active; if the fraction of work perceived complete is under 25%, the workers are working on an average of two floors area; if the progress is over 25%, about 1/6 of the total expected area is assumed available

3.2 if the perceived progress of construction is still 0%, the ratio is set to 200 square feet per worker for plotting purposes (no effect on productivity);

So, it is necessary to evaluate the number of floors of the building without specifying this number; in taking into account the initial quantity of work, the total work added, the cost per worker per week (5 days* (8 hours/day)*$20/hour), the expected percentage of the workforce cost in the total project cost (33%), the average construction cost per square feet ($85), the gross productivity and the area of one floor in assuming that each floor has the same area, the number of floors is known. These variables must be calculated in a "scalar" built-in function to add all the similar data. The units of these combined factors must be compatible:

$$\frac{\text{const. jobs} * \frac{\text{hours}}{\text{week}} * \frac{\$}{\text{person-hour}}}{\frac{\$}{\$} * \frac{\$}{\text{square foot}} * \frac{\text{const. jobs}}{\text{person-week}} * \frac{\text{square foot}}{\text{floor}}} = \text{floors}$$

4. the overtime effect on productivity;
this variable is described in the Tarek's model, but the equations developed are not the same and they are detailed to consider the possible interferences between the specialties. If there is overtime in the construction process, the rate of increase of the apparent progress goes up: more hours worked mean more work done, but when the workweek is extended, the increase of the progress rate is lower than the overtime increase resulting in a lesser productivity due to exhaustion (see figure 49).

The productivity loss adjusment is not applied to the additional overtime hours but to the total number of hours worked during the time period. The model does not take into account the spot overtime because the productivity decrease is less significant in this case [3].

Overtime hours could be done in these two cases:

4.1 if there is a recognized schedule pressure for the specialty implied and if the manager is willing to work on overtime; the willingness for overtime goes up as the progress goes up. The schedule pressure is evaluated in taking into account the calibrated progress defined in the model in a non-linear table and the actual progress of the specialty. The number of overtime hours is set in a non-linear table that goes up to 10 hours as the schedule pressure goes up (see figure 50).

4.2 if there is a pressure due to the progress of the succeeding specialties involved in the construction progress and if the manager is willing to work on overtime due to the progress of the succeeding specialty. In the model, if the progress of a succeeding specialty has the same progress than the concerned specialty, the workforce of this succeeding specialty stops their work and waits (no productivity). Five equations are defined to take into account the relationships between the specialties:

4.2.1 for the civil specialty, the factor for the overtime is activated if the progress of one of the succeeding specialties (mechanical and architectural work) has the same progress than the civil specialty

4.2.2 for the mechanical specialty, the factor for the overtime is activited if the progress of the succeeding specialty (the electrical work) has the same progress than the mechanical specialty

4.2.3 for the electrical specialty, the factor for the overtime is activited if the progress of the succeeding specialty (the interior work) has the same progress than the electrical specialty

4.2.4 for the architectural specialty, the factor for the overtime is activited if the progress of the succeeding specialty (interior work) has the same progress than the architectural specialty

4.2.5 for the interior specialty, the factor for the overtime is not activited because it is the last specialty involved in the process.

5. the job size effect on productivity; the job size has a significant effect on productivity in major projects. This productivity multiplier goes down from 1.00 to 0.92 when the number of manhours on the construction site increases from 600,000 manhours to 1,000,000 manhours [3] (see figure 51).

5.6.2.8 Construction Workforce

In a construction project, the workforce needed for each specialty is a ponderation between the indicated workforce and the actual workforce [25]. The desired ponderation could change during all the construction process; for instance, if the progress reaches the end, the manager could desire to be stuck with the actual workforce. The willingness to change the workforce is in relation with the perceived construction progress; if the willingness goes up to the value "1" (which is the case in the base model), the manager wants the indicated workforce which is in relation with the trapezoidal distribution; if the willingness goes down, the manager is less willing to hire workers (see figure 52).

The ratio of the effort perceived remaining to the time remaining results in a rectangular distribution of the indicated workforce; to have a trapezoidal distribution, the ratio must be multiplied by the required trapezoidal factors which take into account two parameters (see figure 53):

1. the recognized number of workers requested in regard to a rectangular distribution;
2. the effort perceived remaining with a trapezoidal

distribution in regard to the effort perceived remaining with a rectangular distribution.

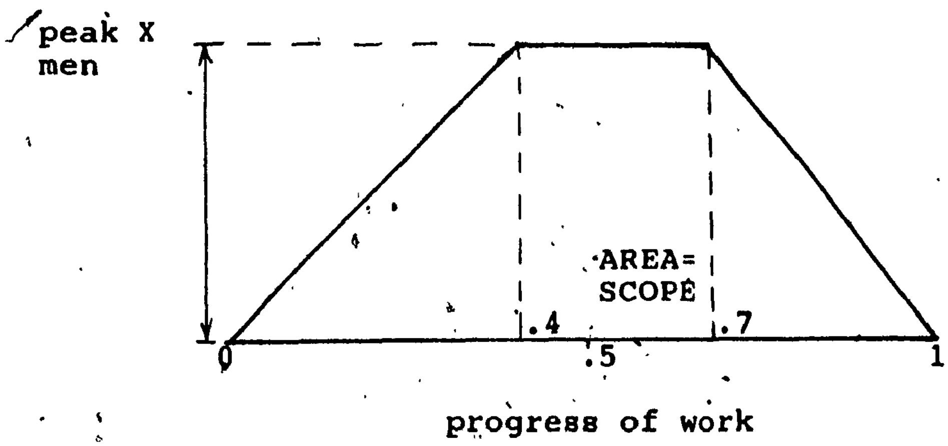


figure 53. Trapezoidal distribution of workers

In the model, there is another variable that identifies the indicated workforce that, furthermore, takes into account the relations between the specialties in order to inform the manager that overtime or waiting time is necessary; this is done with a multiplier to the indicated workforce of the correponding specialty:

1. for the civil work, there is no specific relation between the specialties because the work starts with this specialty and can be completed without the need of another specialty; the only consideration is that, if the actual time is equal or greater to the construction start date, the

multiplier takes the value "1" meaning that the civil work can go ahead with the indicated workforce

2. for the other specialties, the multiplier factor for the indicated workforce taking into account the relations between the specialties has the value "1", meaning that the management is willing to go ahead and wants to start or continue its work with workers, if the following respective elements are true; otherwise, the multiplier has the value "0", setting the indicated workforce to "0" (see figure 54). The multiplier factor for the indicated workforce is "1" if the following conditions applying to each specialty are true:

2.1 for the mechanical work:

2.1.1 if the progress of civil work has reached at least the fourth floor or the last floor (if the building is lower than 4 floors); in this last case, the mechanical work does not start before the end of civil work;

2.1.2 if the civil construction progress is equal or greater to the mechanical progress;

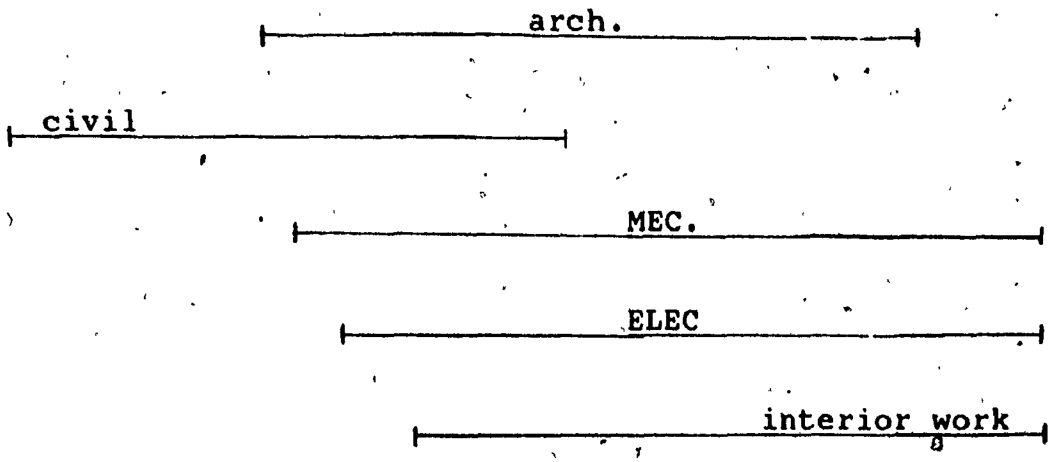


figure 54. Bar chart of activities sequencies in construction

2.2 for the electrical work:

2.2.1 if the difference between the mechanical and electrical work is equal to or greater than "-10%"; in other words, the mechanical work is ahead on the electrical work;

2.2.2 if the difference between the civil and the electrical work is equal or greater than "0"; in other words, the civil is ahead on the mechanical work;

2.3 for the architectural work:

2.3.1 if the number of floors realized by the civil work is equal or greater than 4 (or the number of total floors if the building is lower than four floors);

2.3.2 if the difference between the civil and the architectural work is equal to or greater than

"-10%"; in other words, the civil is ahead on the architectural work.

2.4 for the interior work:

2.4.1 if the number of floors realized by the mechanical work is equal to or greater than 2;

2.4.2 if the number of floors realized by the mechanical work is equal to or greater than 2;

2.4.3 if the number of floors realized by the architectural is equal to or greater than 2;

2.4.4 if the difference between the mechanical and the interior work is equal to or greater to -10%;

2.4.5 if the difference between the electrical and the interior work is equal to or greater to -10%;

2.4.6 if the difference between the architectural and the interior work is equal to or greater to -10%

The manager can choose to have a ceiling on the workforce level which represents more the reality. The model chooses the minimum workforce between the imposed ceiling workforce or the computed workforce needed. In the base model, the worker's ceiling is fixed at the high value "6000" during all the construction process; so, there is in fact no ceiling on the workforce during the simulation (see figure 55). This variable was not described in the other models.

With the gap between the workforce sought and the actual total construction workforce which is composed by the experienced or new workers, the management can hire new workers or transfer workers. In the model, the construction hiring delay and the assimilation delay are set at 2 weeks; the hiring delay is lower than in the design process.

The level of new workers on the construction project is composed of:

1. the actual level of new workers on the project [31]
2. plus the rate of workers hired [31]
3. minus the rate of new workers that become assimilated and are now called the workers with experience [31]
4. minus the rate of new workers that are transferred because at this time, the manager needs a lesser number of workers on the project [31].

The new workers become workers with experience after an assimilation delay which is set at four weeks; some experienced workers are transferred or fired when the workforce sought is less than the actual total workforce and if there are no new workers to be transferred; in the model, the transfer delay and the average workers employment time are respectively set at two weeks and at 60 weeks. A "minimum" function insures that the number of experienced or new workers transferred can not be greater than the actual level of experienced or new workers [31].

The number of workers on site is computed from the sum of the vector "construction workers per specialty". The total cumulative workforce-days is calculated in accumulating the total construction workforce for each period of the simulation and in considering that there is five workable days per week. Also, the model takes into account the accumulation of man-days if they are due to work on overtime.

For each period during the simulation, the number of total perceived man-days is evaluated from the actual level of man-days and the effort perceived remaining.

5.6.3 Procurement Subsystem

This subsystem was not described in system dynamics literature; the procurement of the right equipments or materials is essential to realize successfully a construction project. The procurement progress is related to the design progress, and the construction progress could be affected by the delivery of material on site; the equations in the procurement subsystem generate these interfaces.

In this model, the percentage of material that can be ordered is function of the design progress; this percentage is lesser than the design progress, particularly at the beginning of the design process; for instance, it is not because the design is 50% complete that 50% of the material could be ordered, it is in relation with the progress of design packages complete. In this model, the assumptions are defined in figure 56; for instance, when the design is 40% completed, only 10% of the material can be ordered.

This subsystem is composed essentially of three levels:

1. the level for the requisitions to be processed
2. the level for the purchase orders to be processed
3. the level for the material delivered on site

When the design is completed, all the requisitions could be processed and the sum of these three levels equals 100%; at the end of the procurement process, the percentage of material delivered on site is then 100%.

The first step in the procurement process is the issuance of material requisitions; the level of requisitions issued is a function of the remaining requisitions that do not have a corresponding purchase order, the rate of purchase orders issued and of the number of new requisitions issued. The equation for the rate of new requisitions issued takes into account four elements:

1. that the total number of requisitions issued is not greater than the quantity of requisitions that can be issued in accordance with the progress of design
2. that no new requisition is issued if they are 100% issued
3. a "clip" function takes into account the willingness of the management to start the issuance of requisitions which will be assumed in general one month before the construction start date
4. that the maximum percentage of requisitions that can be issued is 5%.

The delivery rate of material is a function of the delivery delay which goes down if the quality of shop drawings goes up. Bad quality of shop drawings creates lost of time due to revisions of shop drawings by the contractor (see figure 57).

The quality of shop drawings prepared by the contractor also varies in relation with the average quality of design prepared by the consultants. The better the quality of drawings issued by the designers, the better the quality of shop drawings issued by the contractors (see figure 58).

To analyse the effect of the delivery of material on the construction work, the ratio material on site to the material needed is identified. It is recognized that the quantity of material on site must be greater than the specific quantity of material needed compared to the progress of the work. So, in the model, it is assumed that the percentage of material on site must be at least ten percent greater than the percentage of material needed to not create a reduction in the apparent productivity; the lower is the ratio, the greater is the impact on the productivity (see figure 59). The productivity is affected but the number of workers in the concerned specialty is not affected.

5.6.4 Project cost

The impact of inflation on capital expenditures depends on the spending patterns or "S" curves over the period that the money is spent. All cash inflows and outflows must be measured in consistent units in order to perform an economic analysis. Inflation results in future dollars having less value than present dollars; the cash flows in an economic evaluation must therefore be accordingly adjusted. Thus two types of money must be distinguished:

1. current dollars refer to the actual cash flows occurring during a specific time period
2. constant dollars represent cash flows that have equal purchasing power at all times and are inflation corrected money.

The interest formulas may now be modified to include inflation by carefully differentiating cash flows expressed in current dollars or constant dollars. There is no problem under conditions of no inflation where future dollars are equivalent to present dollars. Constant dollars are escalated with this known financial equation:

Actual dollars = constant dollars * $(1+ e)^n$

where e = escalation rate per period

n = number of periods

In this model, equations integrated in the model generate the total project cost; for each timestep in a simulation run, the design cost is established in taking into account these variables:

1. the total number of designers in all specialties
2. the average hourly rate which is set to 55$/hour
3. the number of working days per week because the timestep is in weeks
4. the number of hours per day
5. the timestep itself because if the modeler modifies the timestep, the quantity of man-hours per timestep is modified
6. the nominal escalation factor; the nominal escalation rate is the rate per period or per timestep that will result in an effective rate per year; if the effective rate is 10% per year, as asssumed in the base simulation, the model evaluates the nominal rate per timestep that will result in a 10% effective interest rate in taking into account the compound interest. The nominal interest factor is derived from this equation:

$$i_e = (1+(i_n/\text{number of periods}))^{periods}$$

where

i_e = effective interest rate

i_n = nominal interest rate

number of periods of capitalization = (48/DT)

then,

$$i_e = (1+(i_n/(48/DT)))^{48/DT}-1$$

$$i_e+1 = (1+(i_n/(48/DT)))^{48/DT}$$

$$\ln(i_e+1) = (48/DT)*\ln(1+(i_n/(48/dt)))$$

$$(DT/48)*\ln(i_e+1) = \ln(1+(i_n/(48/DT)))$$

$$e^{(DT/48)\ln(i_e+1)} = e^{\ln(1+(i_n/(48/DT)))}$$

$$(i_e+1)^{(DT/48)} = 1+(i_n(48/DT))$$

$$(i_e+1)^{(DT/48)}-1 = i_n(48/DT)$$

$$i_n = ((i_e+1)^{(DT/48)}-1)*(48/DT)$$

The same computation is done for the construction cost with the same factors used in design but with specific values; two factors are added to better define the construction cost:

1. if there is overtime, this cost is added to the construction; the hourly rate is assumed to be twice the normal rate
2. a procurement factor is included to add the equipment and material cost to the construction cost; the assumption to define the factor is that for each man-hour spent, the total cost including the material, will be about three times the man-hour cost [3].

An effective escalation rate set to 5% per year is used in the base model to convert in current dollars the project cost. The total cost is not only composed of the value of design and construction costs but also of interest payments done for the borrowed money during the design and construction processes. So, the financial payments are also escalated in using the nominal interest rate to have the total project cost in current dollars.

For each timestep, the cost in current dollars is converted in constant dollars in using the nominal interest rate. These variables introduced in the model give the opportunity to analyse the cost of a project for various scenarios: for instance, a period of high interest rate and low inflation or a period of low interest rate and high inflation.

CHAPTER VI

SIMULATIONS

First of all, simulations have been done on a main frame computer; few months later, the softwares MICRO-DYNAMO and Professionel-DYNAMO have been used before to return on a main frame located at the Ecole Polytechnique.

A variety of "what-if" scenarios is explored, based on the initial assumptions to not only discover which factors are most significant to the behavior of the system, but also to better understand how a change to one part of the system affects the situation. Behavioral sensitivity refers to the degree to which the behavior exhibited by the model changes when a parameter value is changed or an alternative formulation is used.

No parameter in a model has a unique value that fits the real system; a range of meaningful values is usually possible. In these simulations, the exact figure is not very important, the understanding of the advantage to select a policy is more benefit.

DYNAMO is designed to allow C (constant) and T (table) statements to be changed (including initial value) in rerun mode, without rewriting and recompiling the model and let you see the results in graphical or tabular format; the graphical format is always related to time and gives the opportunity to accelerate or disaccelerate a phenomenon.

This chapter presents the results of simulations with a conventional project and a fast-track project:

1. simulations with a conventional project which means that the design is complete before the construction starts; it is call the base simulation:

1.1 the base simulation: a conventional project (see figures 60 to 67, tables 7 and 23 for run B). In the conventional construction scheme, the design of the 750 drawings is completed before the start of construction on a building having about 30 floors, as the base simulation. The escalation cost on material and manhours, and the interest rate are set at 5% and 10% respectively. All the estimates are in constant dollars.

The procurement starts 5 weeks before the start of the construction, the construction starts 45 weeks after the start of design. The schedule completion date for overall construction initially is 110 weeks. In the simulation, the construction finished date is 7 weeks later than the initial completion date. The cost total of human resources is evaluated to 66 million $.

Several policy parameters could be modified in the model with possible interpretations of parameter changes:

1.2 Modification in the original model of QD and QC, the quality during the design and during the construction, which are set in tables to normal quality values (see figures 68 to 70, tables 8 and 23 for the simulation L)

A small reduction is possible with the effect of these two factors:

1. The workforce experience which is between .9 and 1
2. The schedule pressure effect on quality which is 100% effective only if the project is at least 60% complete.

When the quality factor in design or construction equals one in these equations, there is less undiscovered rework generated; the workforce with experience and schedule pressure can still modify the quality. The total number of hours is reduced of about 80 000 hours, a reduction of about 7%.

In the model, the new factor for the quality increases the indicated productivity; the manager is willing to recognize the level of work not needing to rework (which is affected by the quality) as the progress goes up. So the result of this simulation is not surprising. It is better to have a better quality control in order to reduce the rework in design and construction.

1.3 Simulation with the gross productivity two times the gross productivity of the base run (see figures 71 to 72, tables 9 and 23 for run R)

If the gross productivity is changed, the strength of the power to produce is reduced, but the hiring loop compensated in adjusting the number of persons and then leaving the behavior unchanged. The total cost is about 32 million and required about 69000 man-days.

Compensating feedback is a property of real systems: a parameter change may weaken or strengthen a feedback loop, but in the multi-loop nature of a system dynamics model, there are compensating feedback loops to keep the behavior unchanged; real systems tend to be resistent to policies designed to improve behavior.

Engineering feedback control systems were developed for precisely the purpose of creating systems that are insensitive to parameter changes by compensating.

This is a place where intervention would have a significant effect. In a feedback structure, a loop that is primarily responsible for model behavior over some time interval is known as a dominant loop. Changing a parameter in a feedback loop creates a greater modification to the system but not on the model behavior.

1.4 Simulation of a conventional project with an immediate schedule adjustment (see figures 73 to 75 and tables 10 and 23 for run E)

The schedule adjustment times meaning speed reporting of progress; quicker response to changes in productivity; less delay in responding to pressure to change the scheduled completion date

The net rate equation is described normally in the form:

(GOAL.K-LEVEL.K)/Adjustment time.

So, making the adjustment time in a huge formulation sets the rate essentially to zero; thus the level never changes from its initial value throughout the run.

Because of the willingness to postpone the schedule when the manager perceived a slippage, the construction was about 96% completed at week 200 and the expected time to complete the project was week 238. The project costs about 10% more than in the base run and requires more man-days.

The schedule completion date is used to compute the indicated workforce; so, because the schedule is continuously adjusted, the level of workforce goes ~~up~~ less rapidly and has a lower peak of workers, compared with the base run. Also, the apparent productivity goes up smoothly because one of the productivity multiplier, the learning effect, goes up smoothly. In fact, the learning effect goes up as the fraction perceived completed of progress goes up, the perceived progress being in relation with the level of workforce.

1.5 Simulation with a conventional project and a fixed construction schedule policy (see tables 11 and 23 for run F).

As expected, the construction is completed in week 111, the initial schedule completion date; but the construction required more man-hours to meet the target date. When the project is near the end, there is a schedule pressure effect on quality and productivity.

The manager can then evaluate the additionnal cost or required cost to fix or advance the target date.

1.6 Simulation with a conventional project and a fixed construction schedule policy and a ceiling on designer workforce (see figures 78 to 81, tables 12 and 23 for run G)

This simulation is the same as run F, except that there is a ceiling on the designers workforce; it is the same number of man-hours in both cases but this simulation costs 0.6% more. This designers ceiling is a better representation of the reality; the designers become more experienced as the progress of the project increased and the quality of design is better. Then, the drawings are finished in less man-hours.

Also, even if the design completion date is the same as in the other runs, the centroid of designers moves to a later date, modifying the the cost (present worth) of the design phase: it results in a lower value taking into account that the interest rate is 5% higher than the escalation rate.

1.7 Simulation with the conventional approach with a ceiling on design and construction workforce and a fixed schedule in design and construction (see figures 82 to 84, tables 13 and 23 for run K)

This simulation gives about the same result as simulation G (where there is a ceiling on designers workforce only). To be more significant the workers ceiling should have been lower.

1.8 Simulation of a conventional project with a designers ceiling and fixed design and construction schedules and a willingness to recognize the schedule pressure from the beginning of the processes (see figures 85 to 87, tables 14 and 23 for run J)

The management team will push the workers to work faster (to increase the productivity); this will decrease the quality. The design and construction processes are completed at the stipulated date but with 32 000 man-days exceeding the base run. The assumption for the calibrated progress must be realistic to not stress the management where there is no schedule problem.

1.9 Simulation of a conventional project with work added and design change (see figure 88, tables 15 and 23 for the run H)

As it is expected, the design and the construction require more man-hours, material, time and cost more. The manpower was essentially affected in design with a lower quality and a lower productivity due to the effect of work added and design change, of schedule pressure and a lower learning effect due to the destabilization in the activities.

1.10 Simulation with a conventional project and a willingness to be more agressive to hire workers (see figures 89 to 90, tables 16 and 23 for run O)

The project costs more and requires an additionnal 3 600 man-days due to the rapid answer to any fluctuations in the workforce to be hired.

The new workers will have a reduced productivity but the workforce will become rapidly experienced. This additionnal number of hours could be explained by an improductive period at the beginning due to:

1. The design process due to a lack of drawings from the succeeding specialties,
2. The construction, due to a lack of space or material available.

For this period, there is a large number of persons working compared to the base run.

1.11 Simulation with a conventionnal project and the manager is not willing to change the workforce near the end of the design and construction processes (see figures 91 to 92, tables 17 and 23 for run M).

Because the manager wants to keep everybody, it costs more. The reduction of the workforce comes from the workers that quit. The only one advantage is to take less time but at the risk of having an area workload. The project takes 6 400 man-days in addition to the base run.

1.12 Simulation with the conventional approach and the willingness to recognize soon the real productivity in design and construction (see figures 93 to 94, tables 18 and 23 for run D)

In the model, the willingness to recognize the real productivity increases as the progress increases, but the effect to have a better control and to know the real productivity is that the project costs about 3 million dollars more than the base run; the manager recognizes that the productivity is lower at the beginning. This is due principally to the learning effect; then, the manager estimates the effort remaining and the manpower required to hire new workers. These workers are new and have less experience, so the quality is reduced and less good drawings of construction work is done affecting in return the real productivity.

The effort perceived remaining is used to estimate the indicated completion date which affects the schedule completion date. This simulation takes 8 weeks more than in the base run.

1.13 Simulation of a conventionnal project with an inflation rate of 10% higher than the interest rate (5%) (see figures 95 to 96, tables 19 and 23 for the run P)

The completion dates and the duration are the same as in the base run, except that the final cost is higher. This is not a surprise and it will be interesting to analyse fast-track projects with these conditions.

2. Simulations with a fast-track project.

2.1 Simulation of a fast-track project (see figures 97 to 101, tables 20 and 23 for the run C).

Compare to the base run, the only constants modified are the construction start time and the procurement start time which are set on week 25 and 20 respectively. The construction is completed 25 weeks earlier than in the base run but costs about 65,5 million dollars, an additionnal 1,3 million dollars.

Essentially, this additionnal cost is due to more rework done during the construction because the design is not completed (about 40%) and the generation of design needing rework affects the work on the construction site: rework, reduction of quality due to the demoralization of workers, schedule pressure due to total construction jobs higher than expected at the beginning of the construction.

The owner could have revenue from rental 25 weeks earlier resulting in an advantage to fast-track the construction.

2.2 Simulation of a fast-track project with an inflation rate of 15% rather than 10% set in the base run and interest rate of 5% rather than 10% set in the base run (see figures 102 to 103, tables 21 and 23 for the run W)

If this simulation is compared with the run P where the inflation and the escalation rates are the same and the project is conventional. The results of these simulations are:

SIMULATION	TOTAL COST	TOTAL MAN-DAYS
W (fast-track)	76,5 million $	139,000
P (conventional)	79,4 million $	138,000

Even if there are more man-hours and more material cost due to rework in the fast-track, the total cost is 2.9 million dollars lower than the conventional project. In reality, there is a lot of fast-track construction done to save money on account of the inflation rate. It is better to borrow the money and construct now rather than later. When the inflation is lower than the interest rate, it was not worth paying to realize the fast-track construction. But the owner of the building could decide to start the project earlier due to the additionnal revenue from rental or to not lose the market.

2.3 Simulation with a fast-track project, with a fixed construction schedule and a willingness to work on overtime due to acceleration and due to schedule pressure (see figures 104 to 106, tables 22 and 23 for run U)

The workers do overtime not only to complete the rework but also when:

1. the preceeding specialty is reaching the progress of this specialty.
2. the progress is perceived behind the

calibrated schedule during all the construction.

The result of the simulation shows an additionnal 13 000 man-days and 54.4 million dollars compared to the base run.

CHAPTER VII

CONCLUSION

From the causal loop diagram, a system dynamics model helps us to understand the system by placing the variables in a system of relations with one another. The situation in the system is continuously changing due to the perceived situation or need in the previous time. Even if the policy is modified, the behavior modes like the manpower distribution, the cumulative progress, are always the same; there is no oscillation, only the amplitude can be changed. If there is a restrictive policy, in doing overtime for instance, the new loop shifts the burden of control to this new loop.

But the most important finding is that the simulations prove that it is economically advantageous to start the procurement and the construction before the end of the design, in fact, when the design progress of a building project is about thirty-five percent complete. A fast-track construction generates, of course, more redesign, more rework, more stress on the project team, but the owner will receive rental revenue in advance compared to a conventional project; the additional amount is significant and compensates for the additional redesign or rework done during the construction and especially in a period of high interest rate and inflation. For the same reason, the fixed-schedule policy proved to be a good policy; the manager adjusts the workforce level in design and construction in order to complete the project in the stipulated time.

System dynamics model is a powerful tool, not only for managers to exhibit consequences of their alternatives in major projects which involve many variables, or to avoid project disasters, but also to assess impact costs caused by ripple effect on productivity due to disruption of work.

This study should lead to further research using system dynamics thinking in the construction industry because the reality is more complex and the model has limits: for instance, the procurement is not sufficiently detailed for special long deliveries; design change in one specialty affects also the other specialties; the climate imposes a cyclic construction workload. This model is not "the" model, but it proves to react to the reality.

APPENDIX 1

LISTING OF GRAPHS

Listing of Graphs

The most frequently convenient notation used in the Dynamo language for special relationships between variables is the TABLE function. The Dynamo language can interpolate to find the value if it is in the specified range or extrapolate to find the value if it is outside this range; in that last case, the model takes a value given for the extremes.

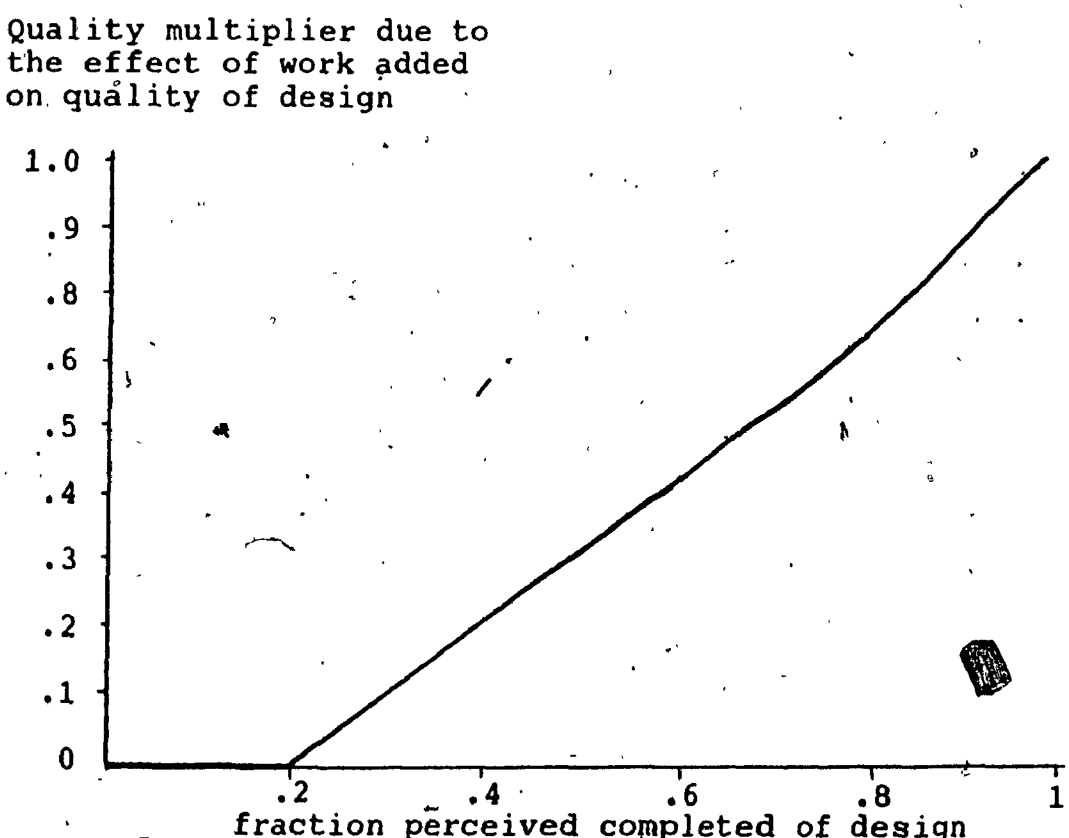


figure 16. Effect of work added on design quality

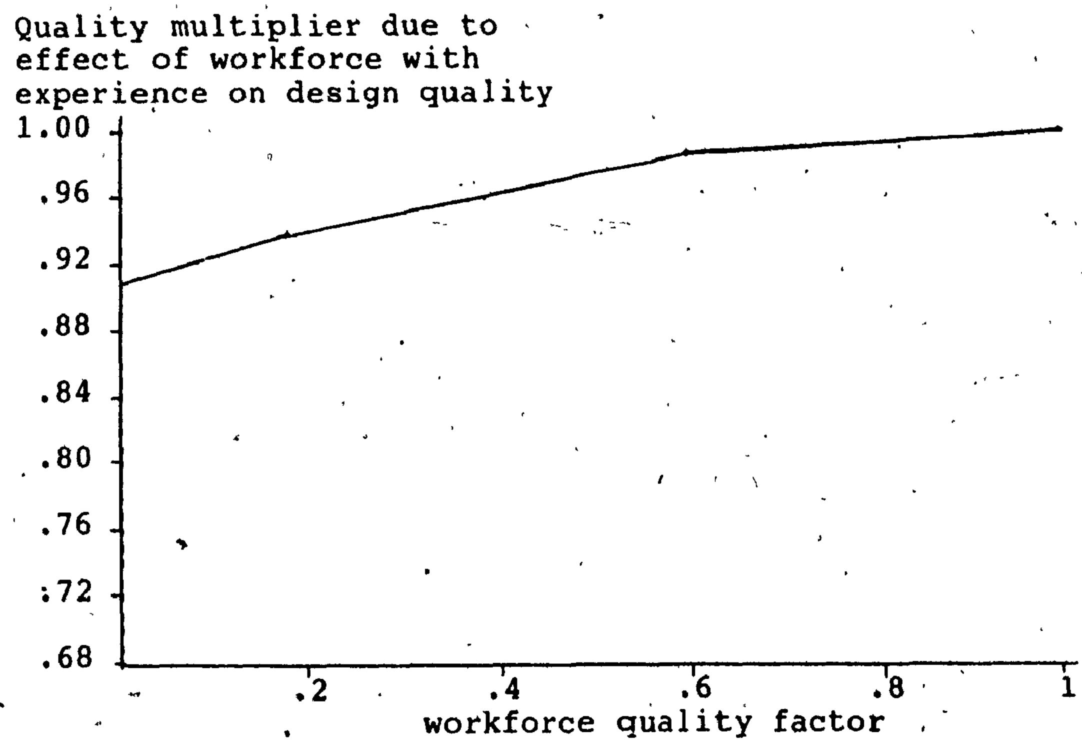


figure 17. Effect of designers with experience on quality

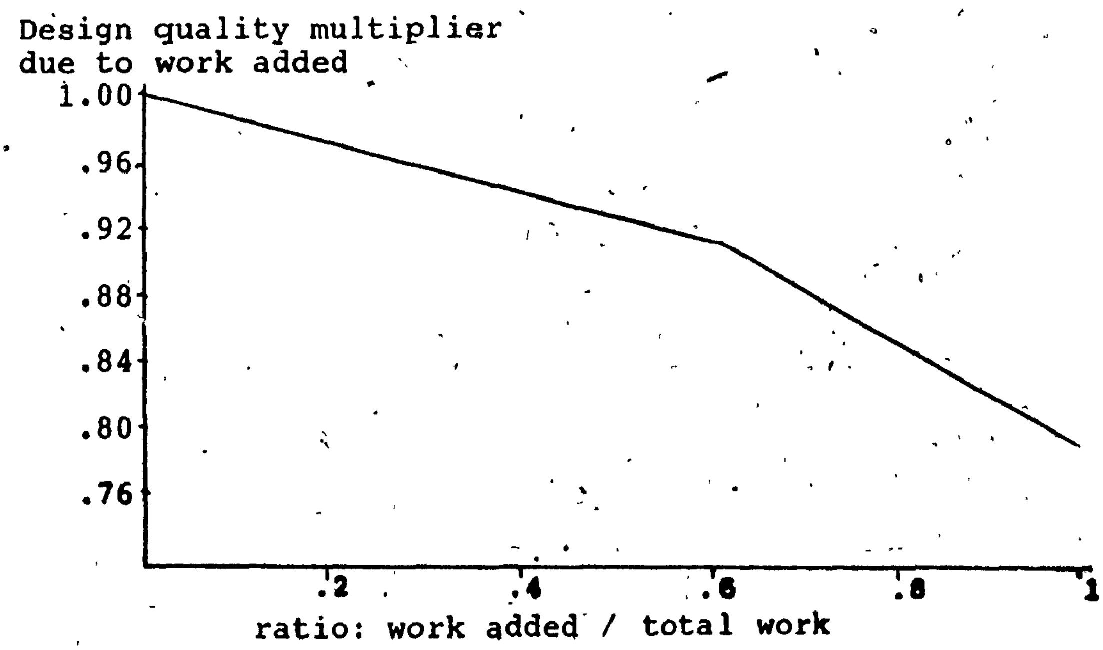


figure 18. Design quality multiplier due to work added

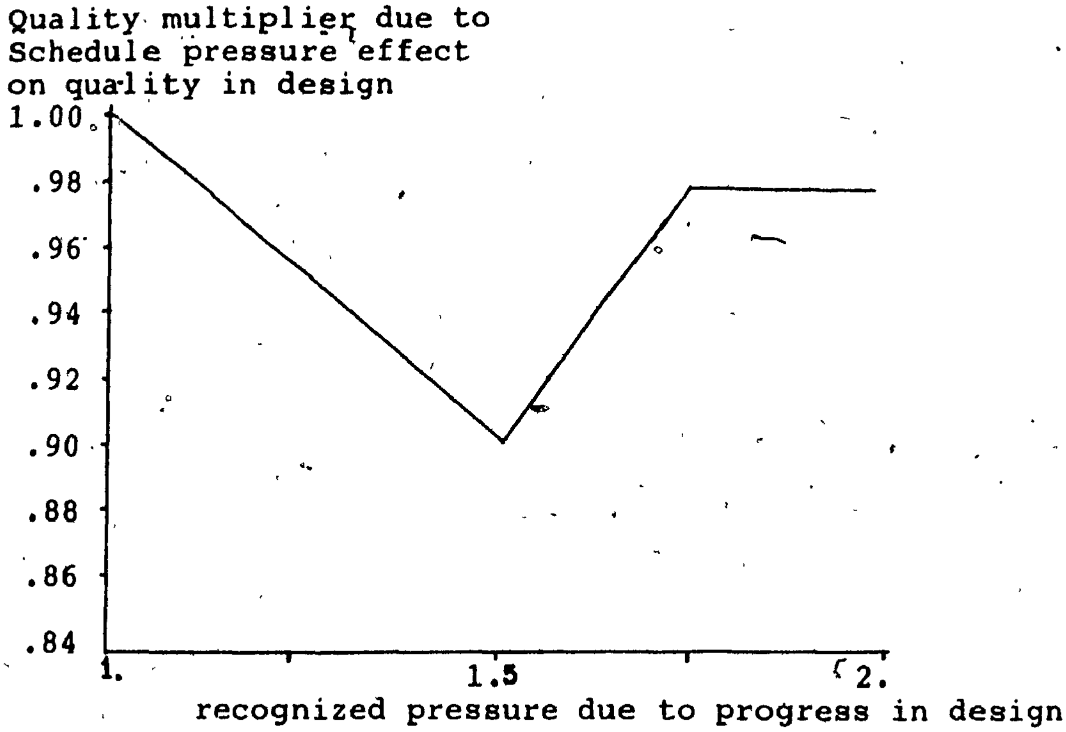


figure 19. Schedule pressure effect on design quality

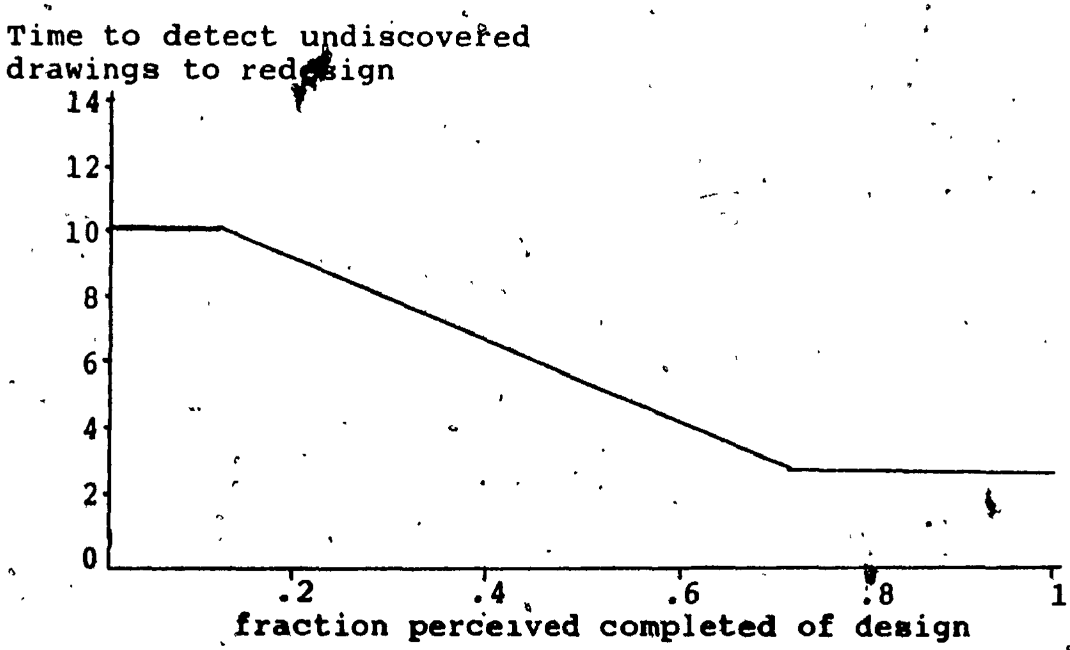


figure 20. Time to detect rework in design

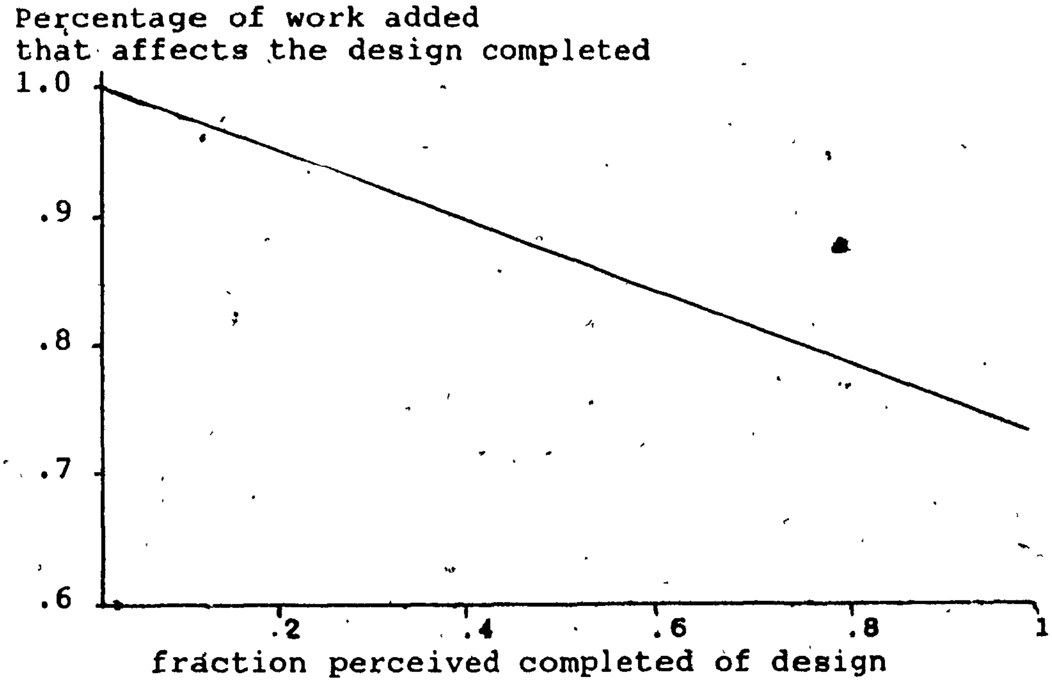


figure 21. Percentage of work added affecting the design completed

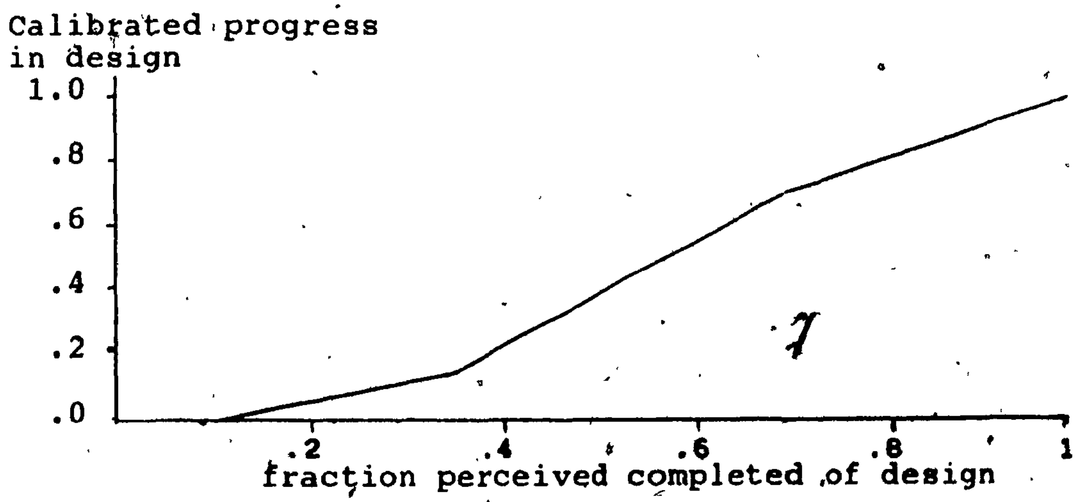


figure 22. Calibrated progress in design

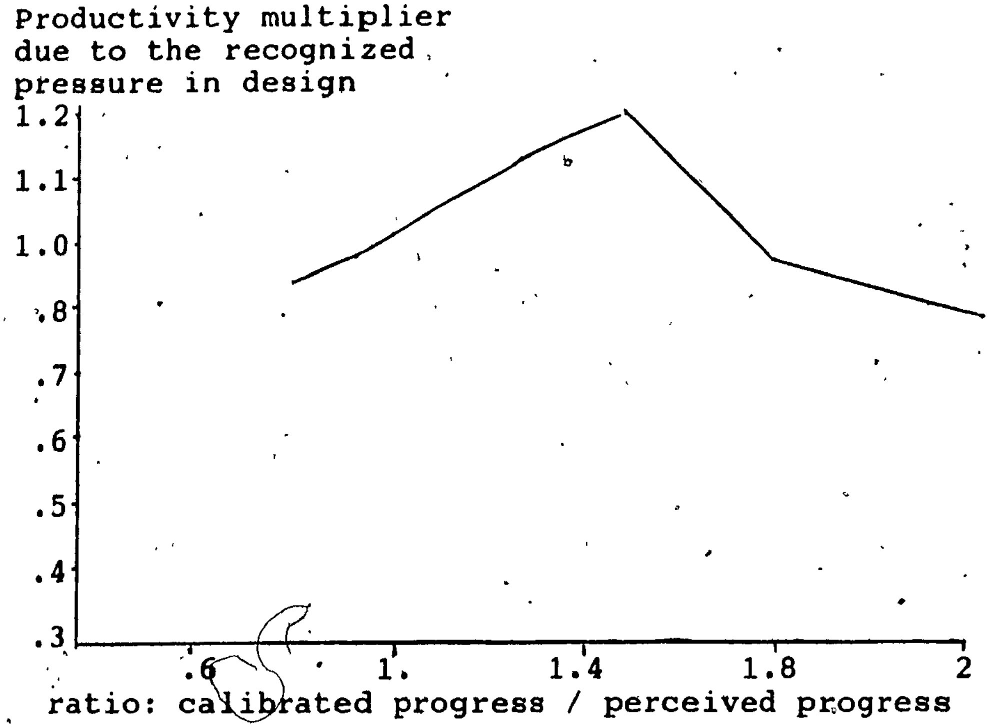


figure 23. Productivity multiplier due to the recognized pressure in relation with the progress in design

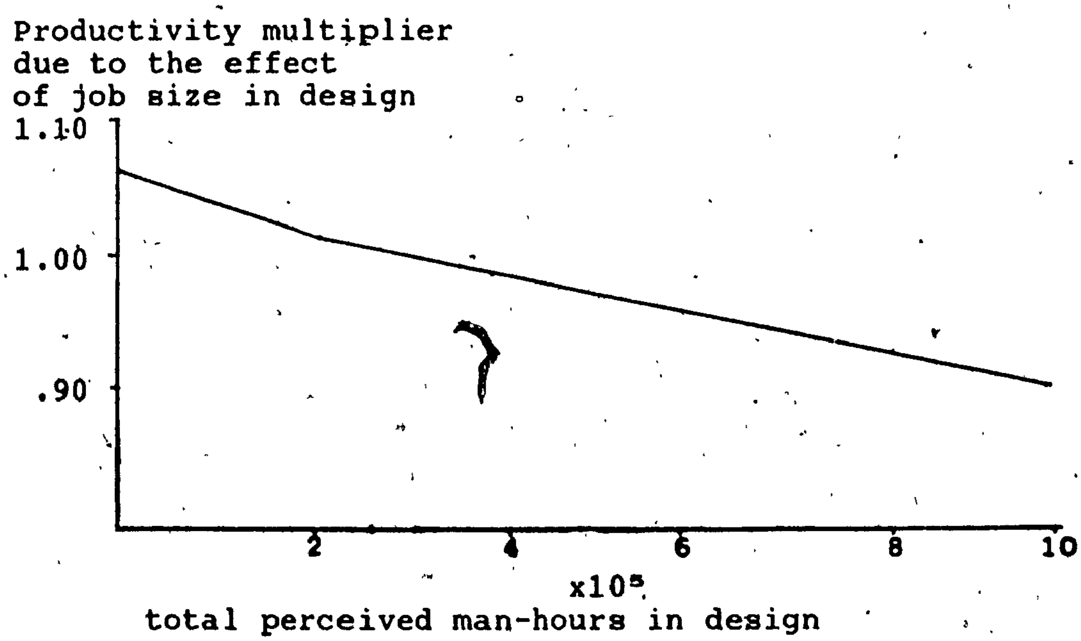


figure 24. Effect of job size on productivity in design

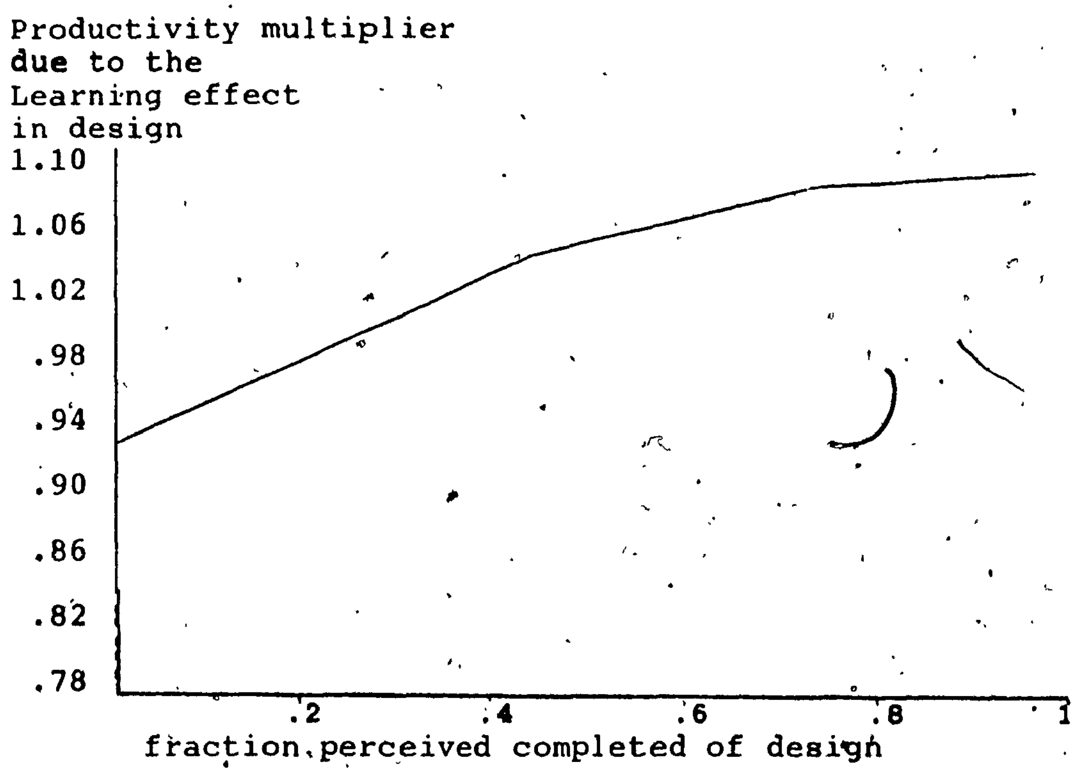


figure 25. Productivity multiplier due to the learning effect on productivity in design

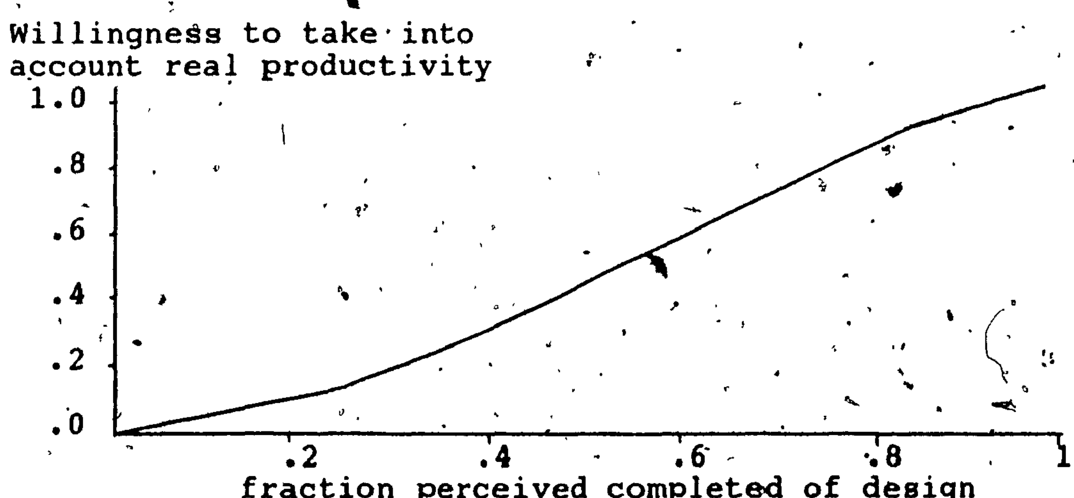


figure 27. Willingness to take into account the real productivity in design

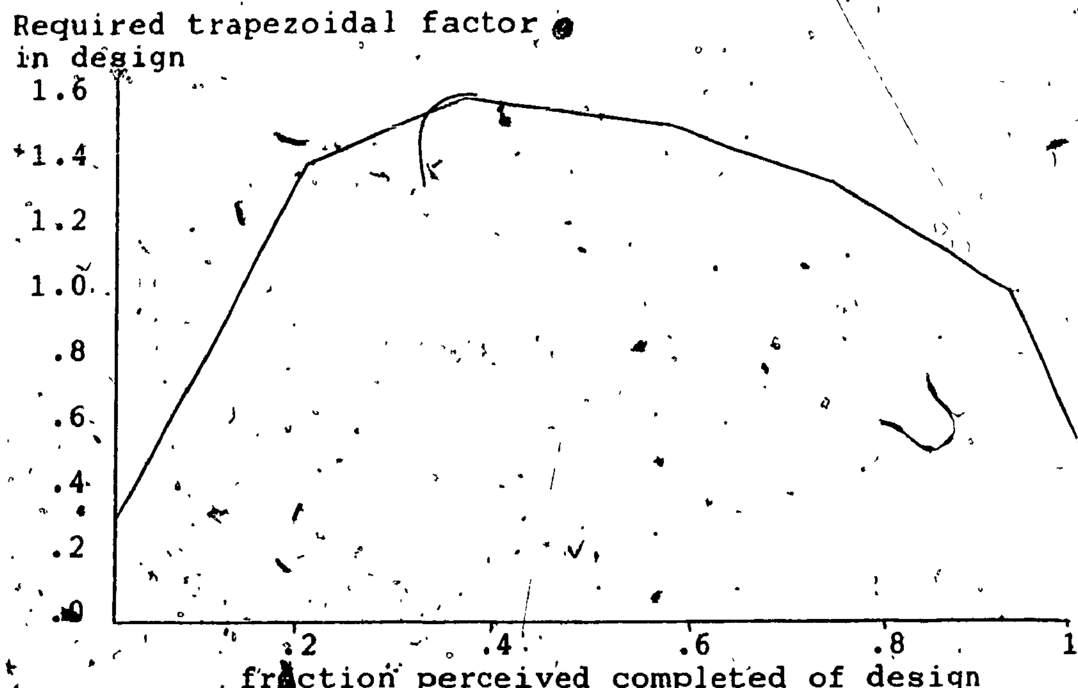


figure 29. Required trapezoidal factor in design

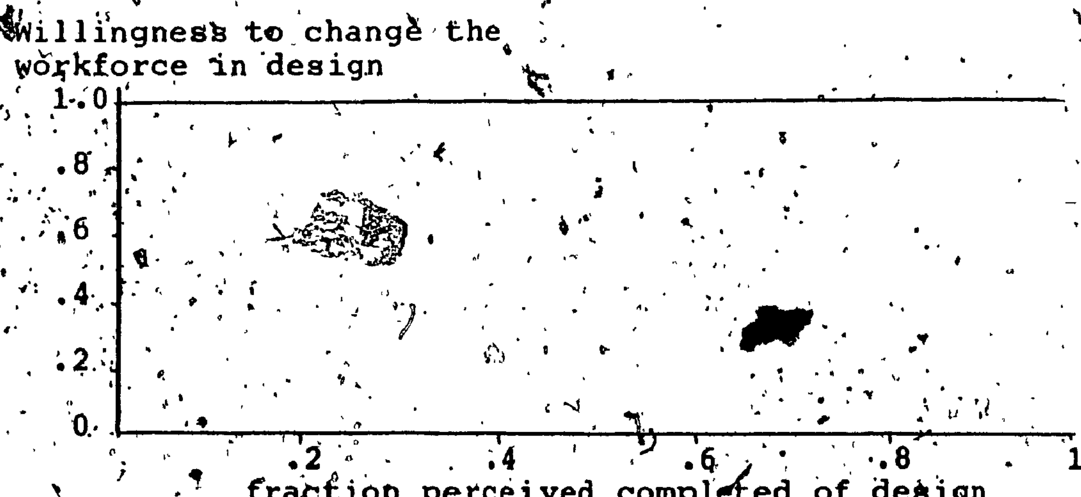


figure 30. Willingness to change the workforce in design

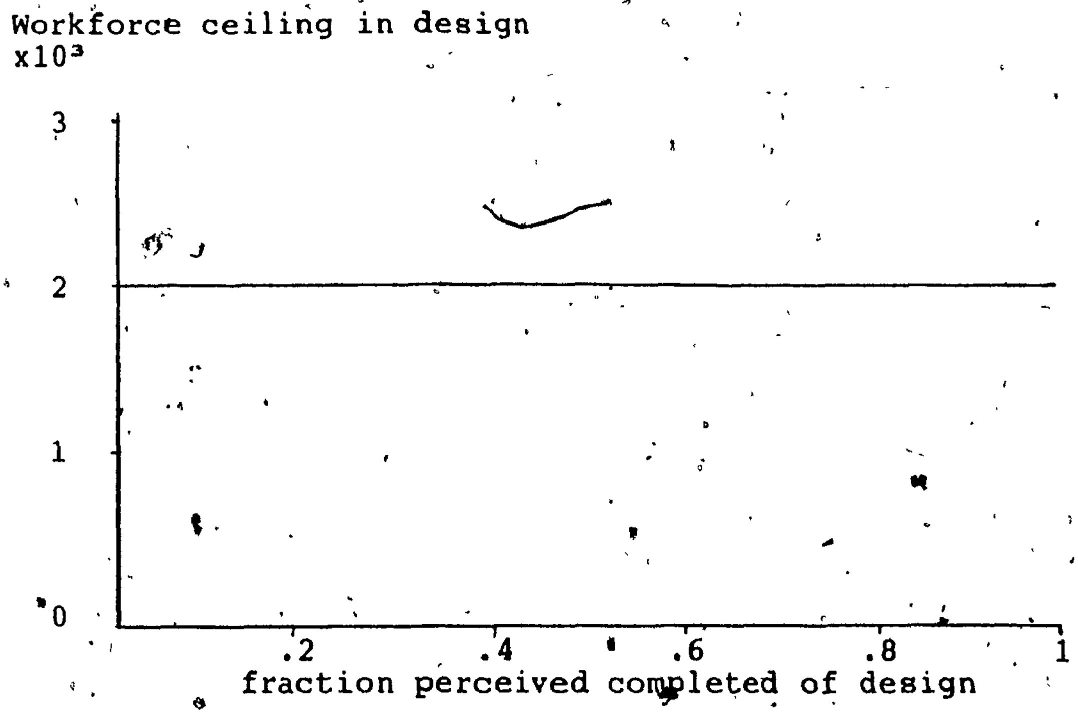


figure 31. Ceiling on design workforce

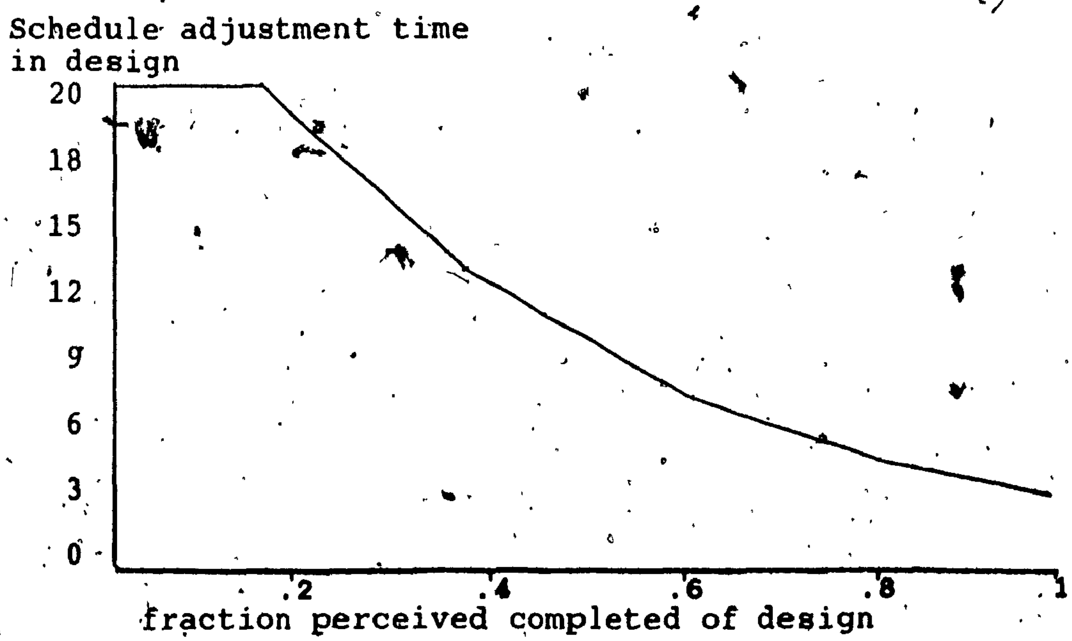


figure 32. Schedule adjustment time
in design

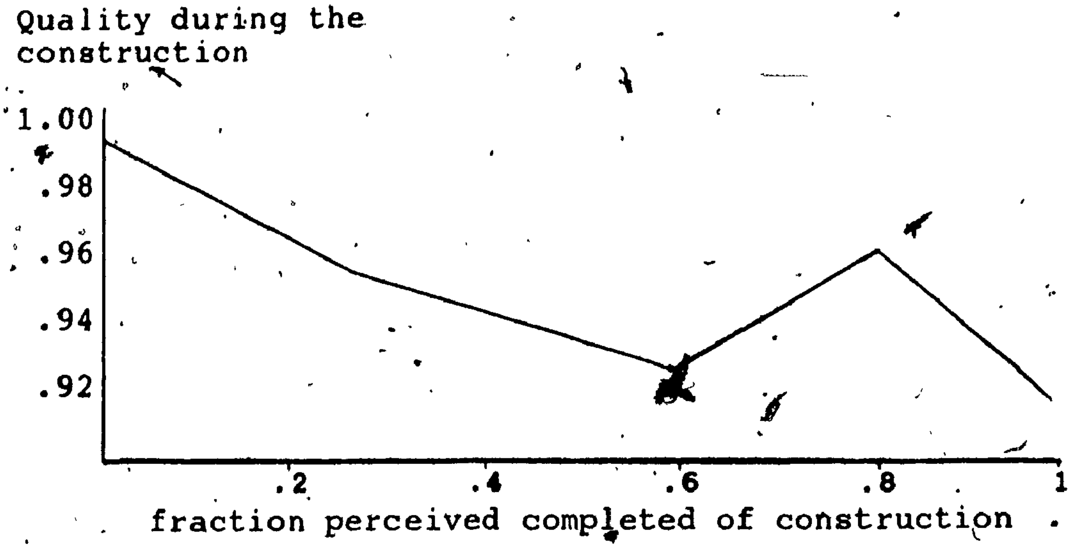


figure 33. Quality during the construction

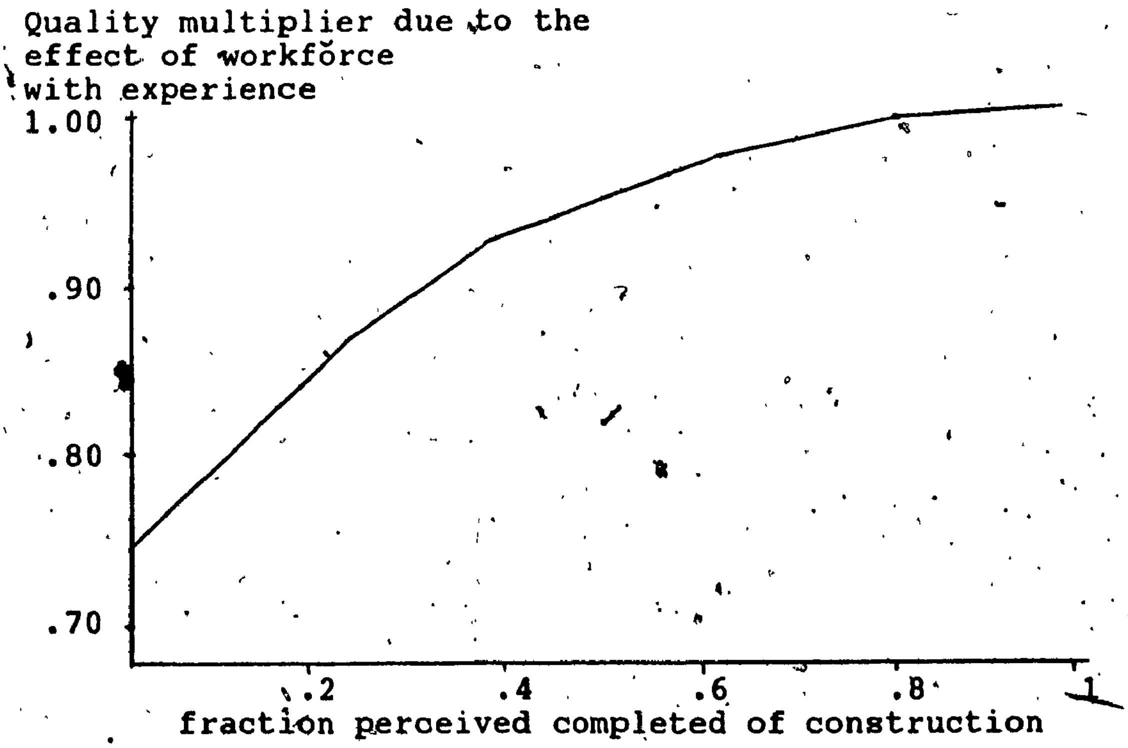


figure 34. Effect of workforce with experience on quality in construction

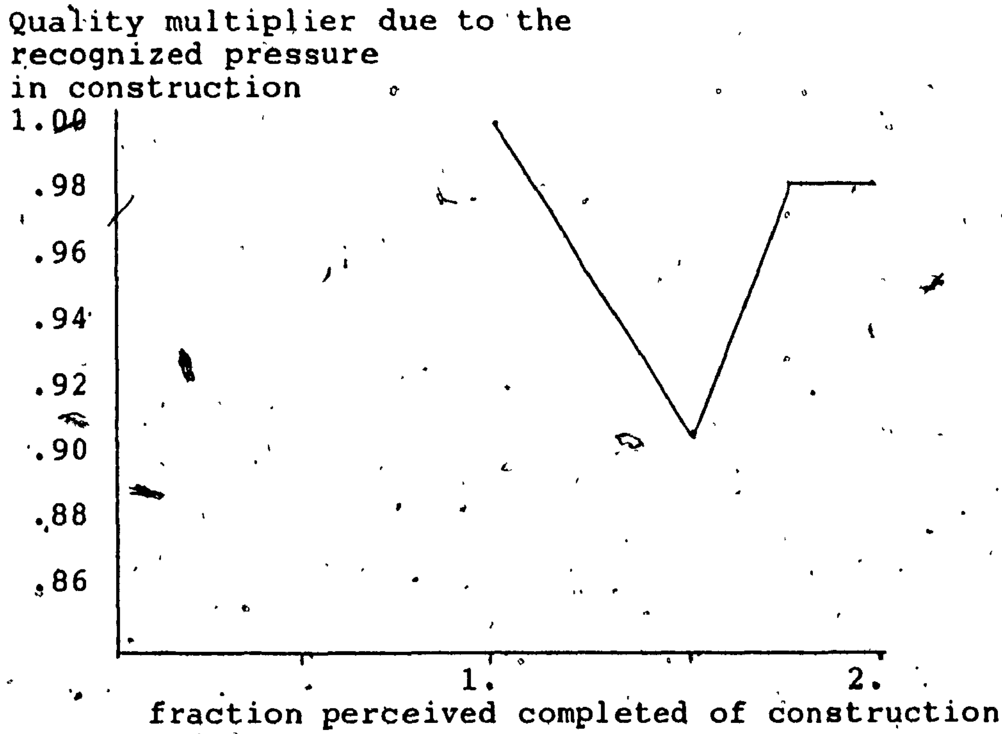


figure 35. Recognized pressure due to perceived progress in construction

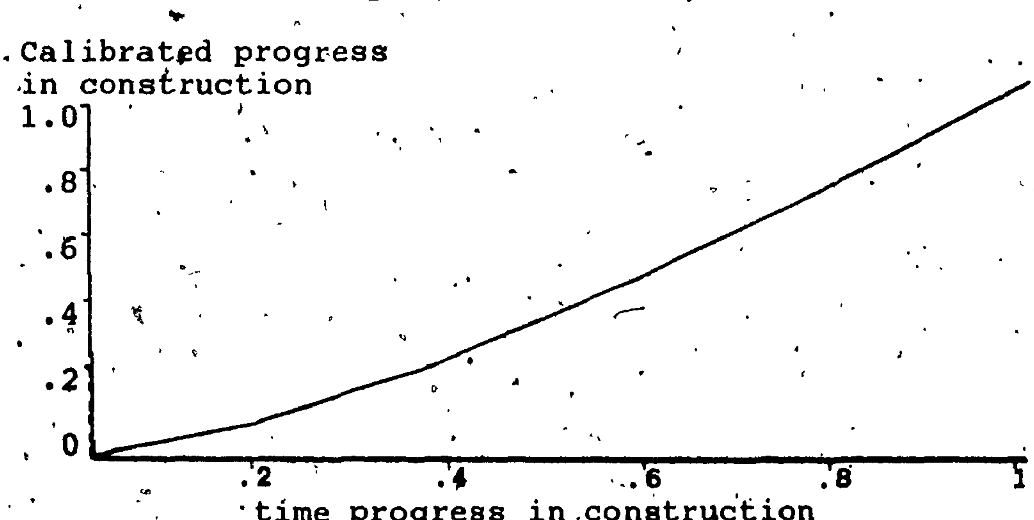


figure 36. Calibrated progress in construction

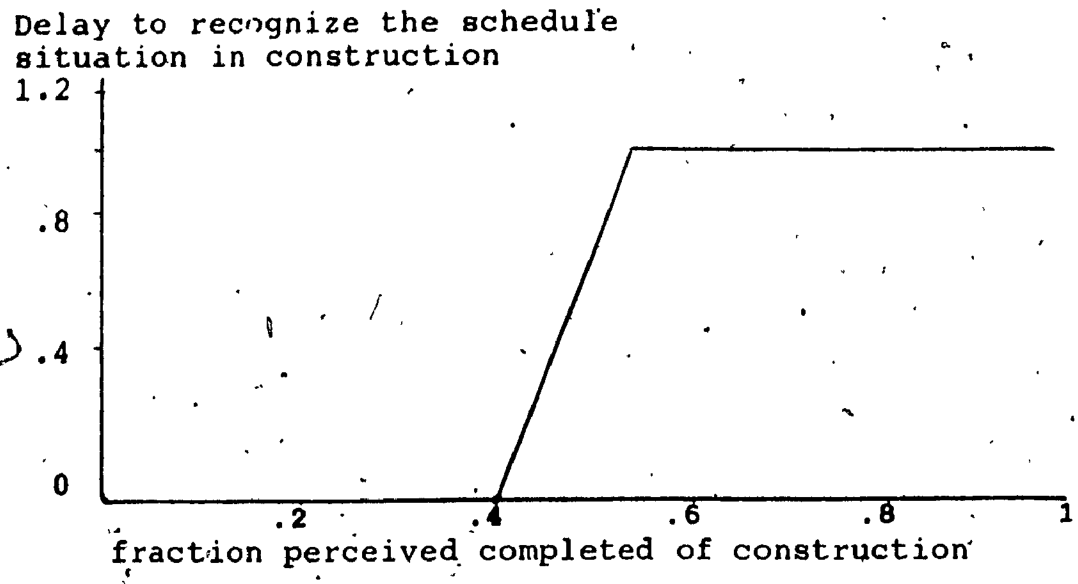


figure 37. Delay to recognize the schedule situation in construction

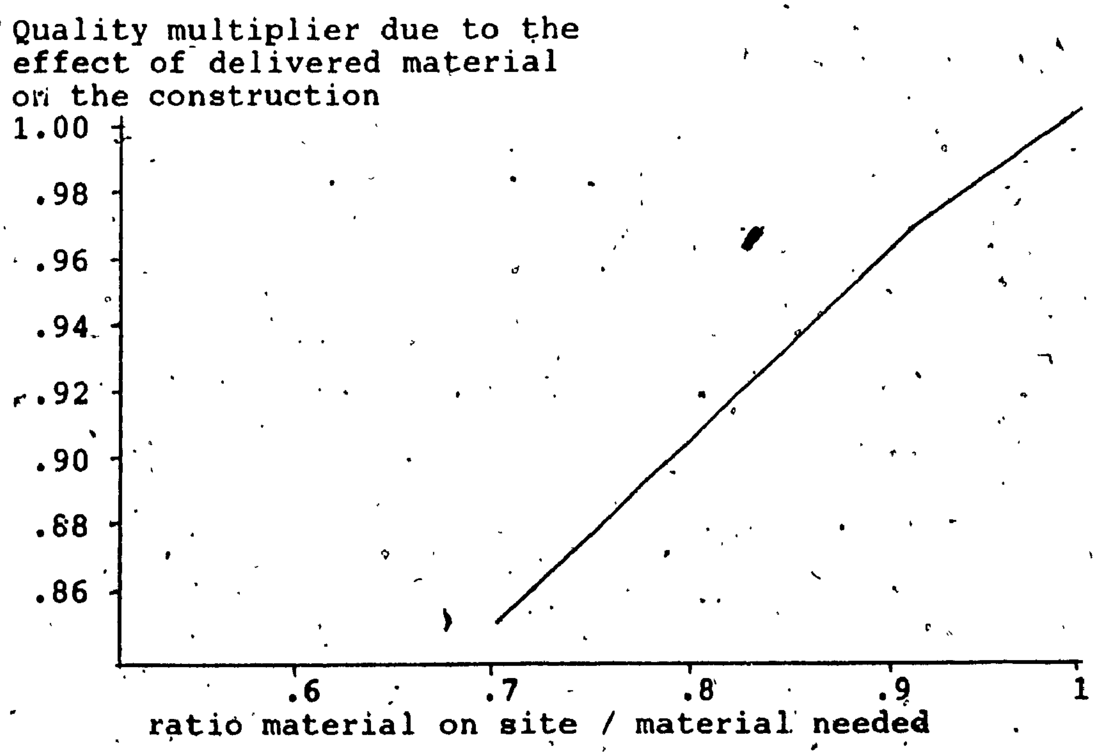


figure 38. Effect of delivery of material on quality in construction

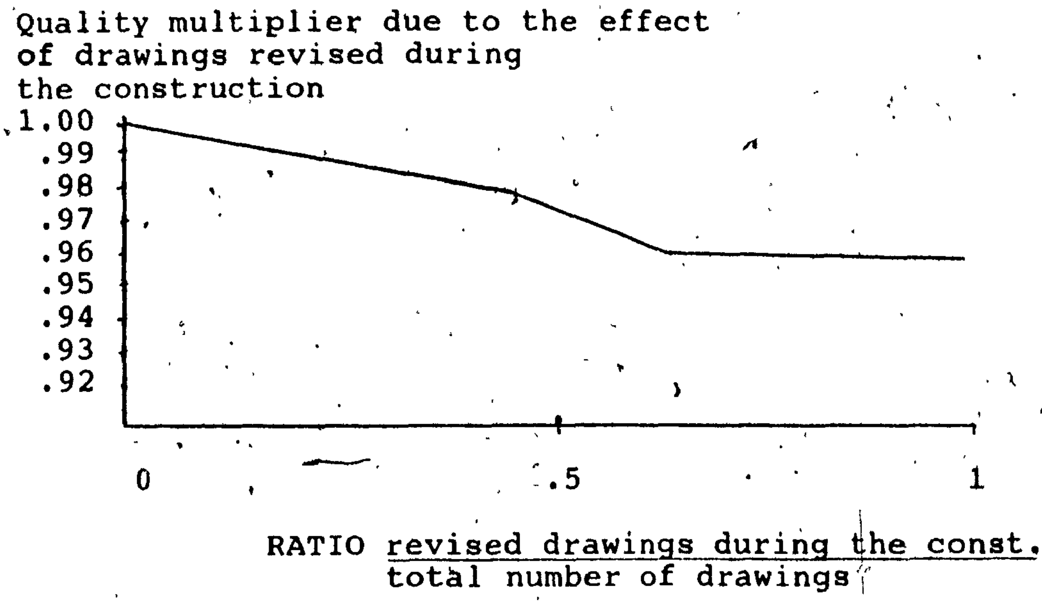


figure 39. Effect on quality due to design revised during the construction

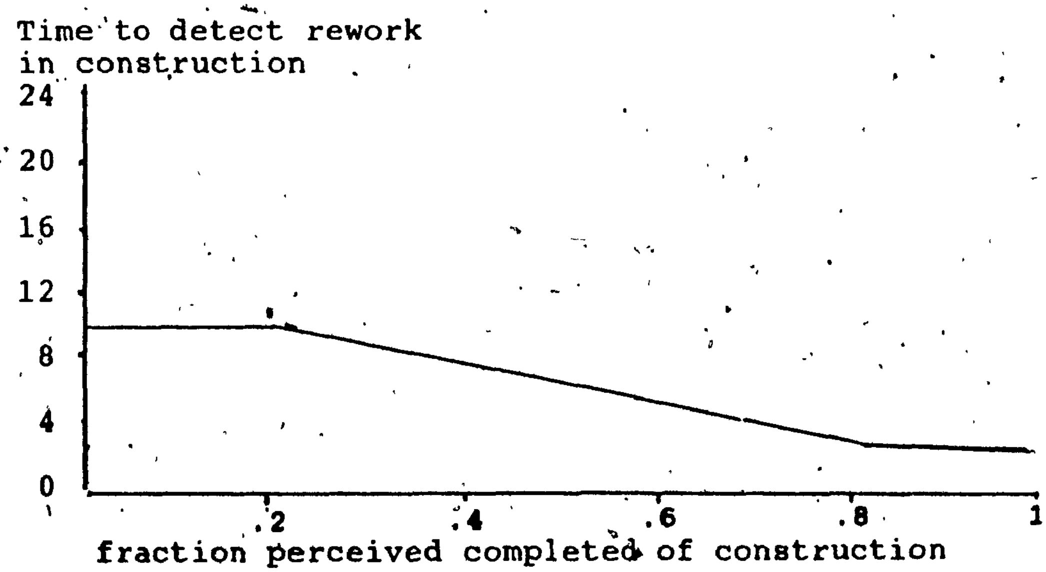


figure 40. Time to detect rework in construction

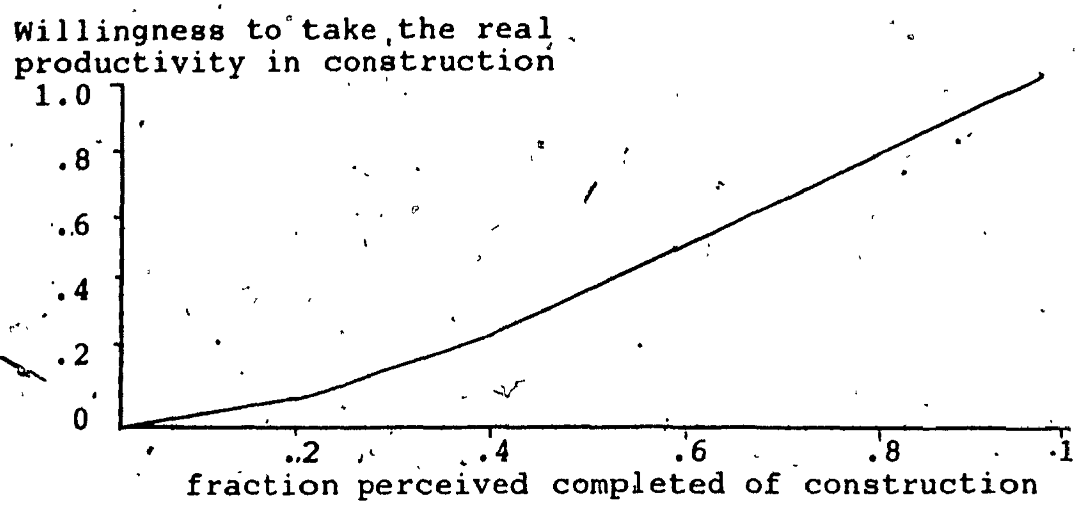


figure 41. Willingness to take into account the real productivity in construction

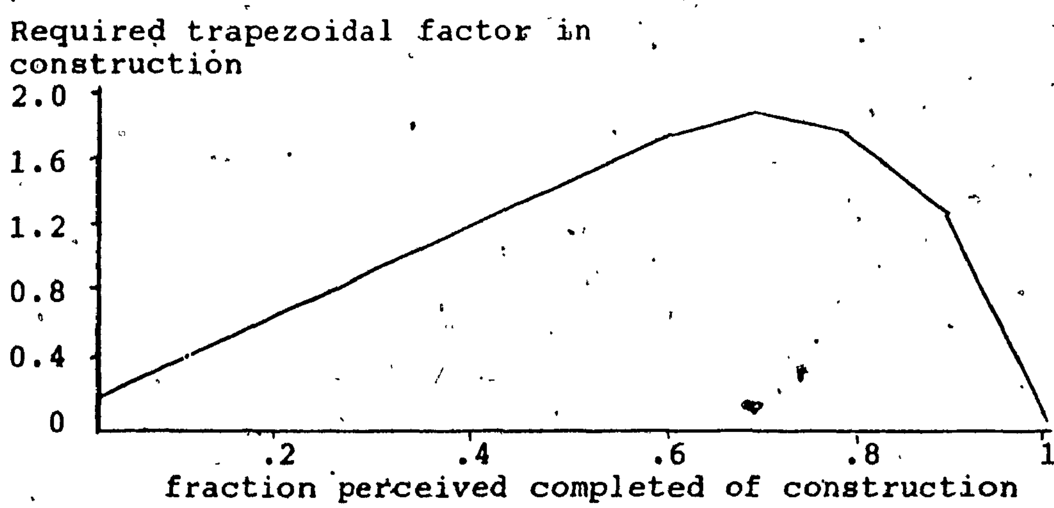


figure 42. Required trapezoidal factor in construction

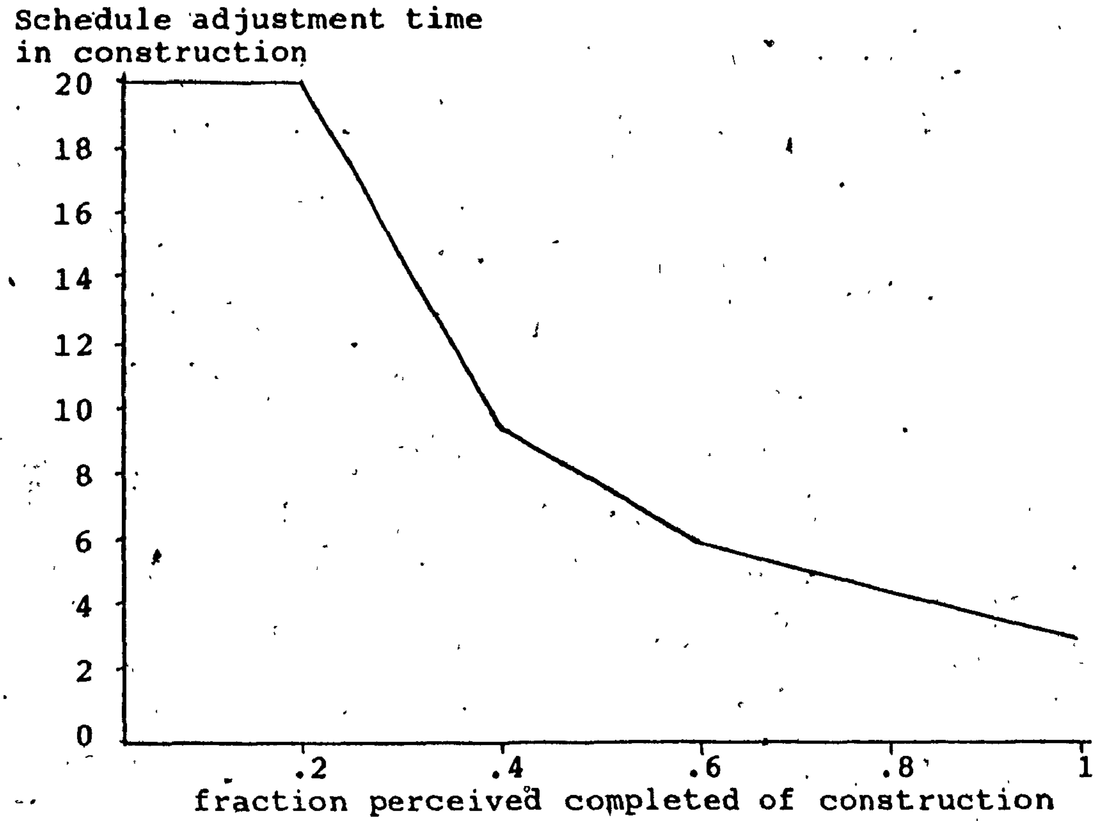


figure 45. Schedule adjustment time in construction

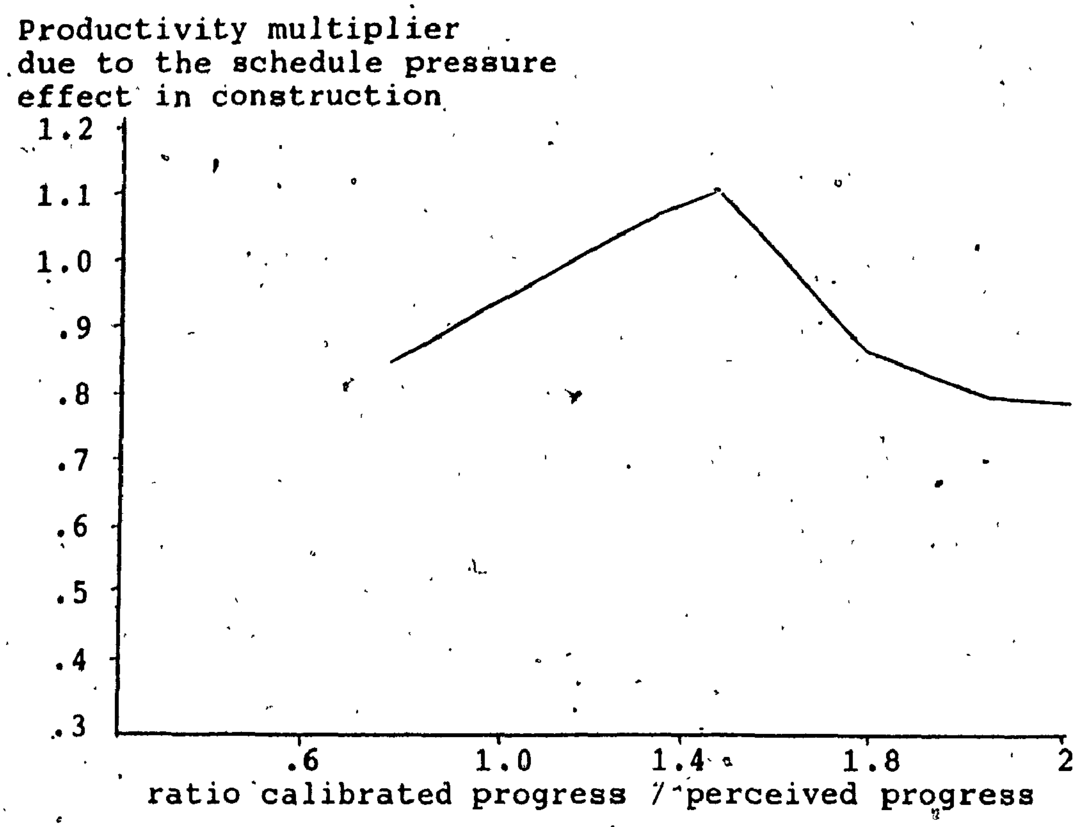


figure 46. Schedule pressure effect on productivity in construction

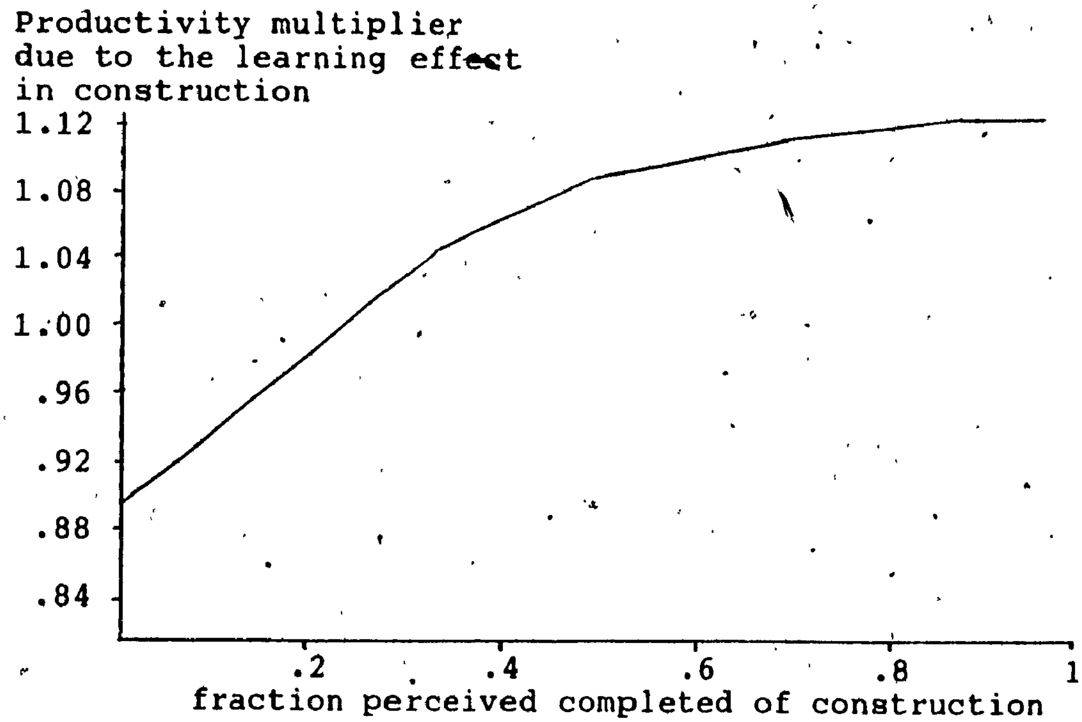


figure 47. Productivity mutiplier du to the learning effect in construction

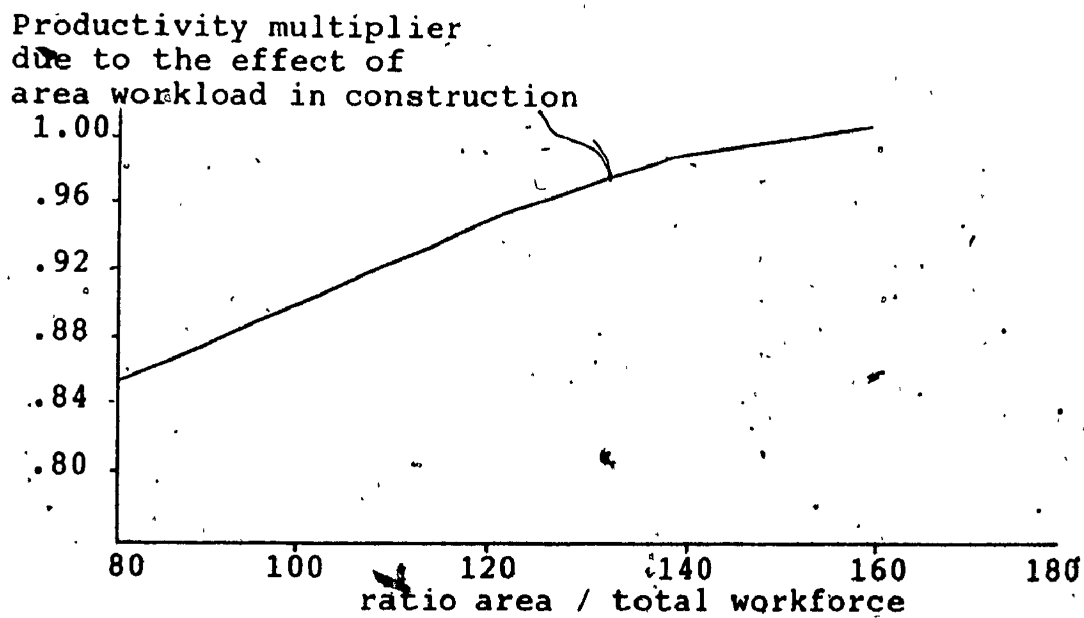


figure 48. Effect of area workload in construction

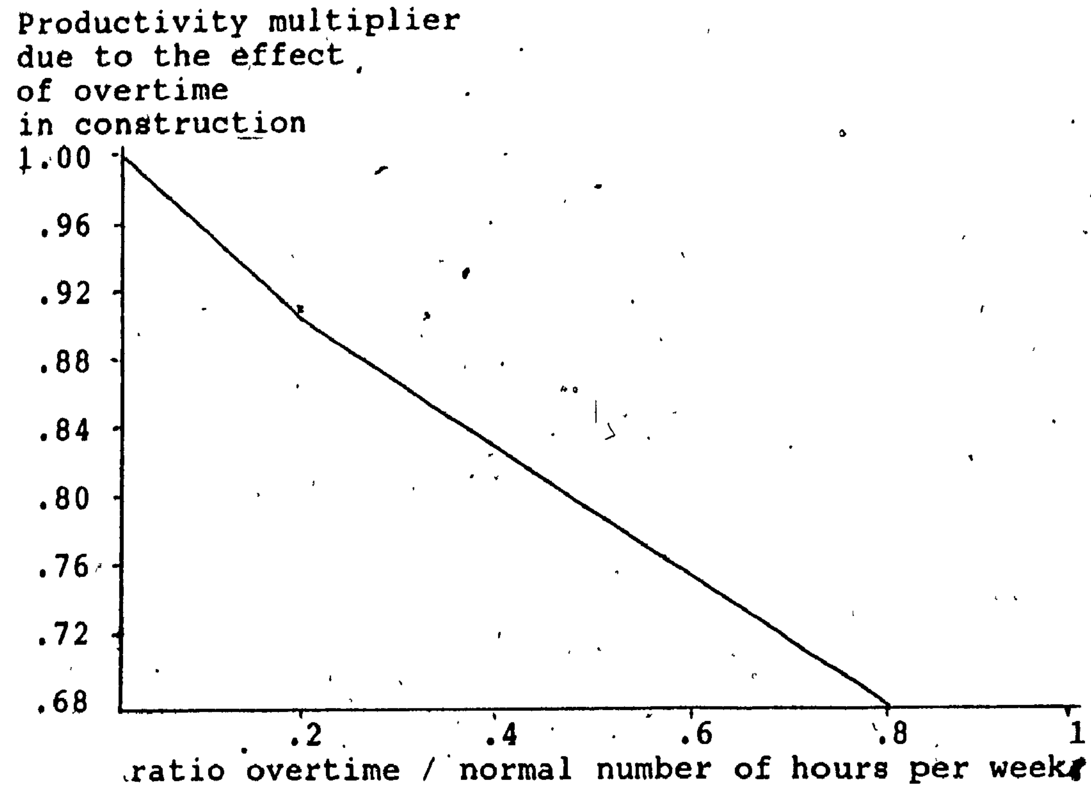


figure 49. Productivity multiplier due to the effect of overtime in construction

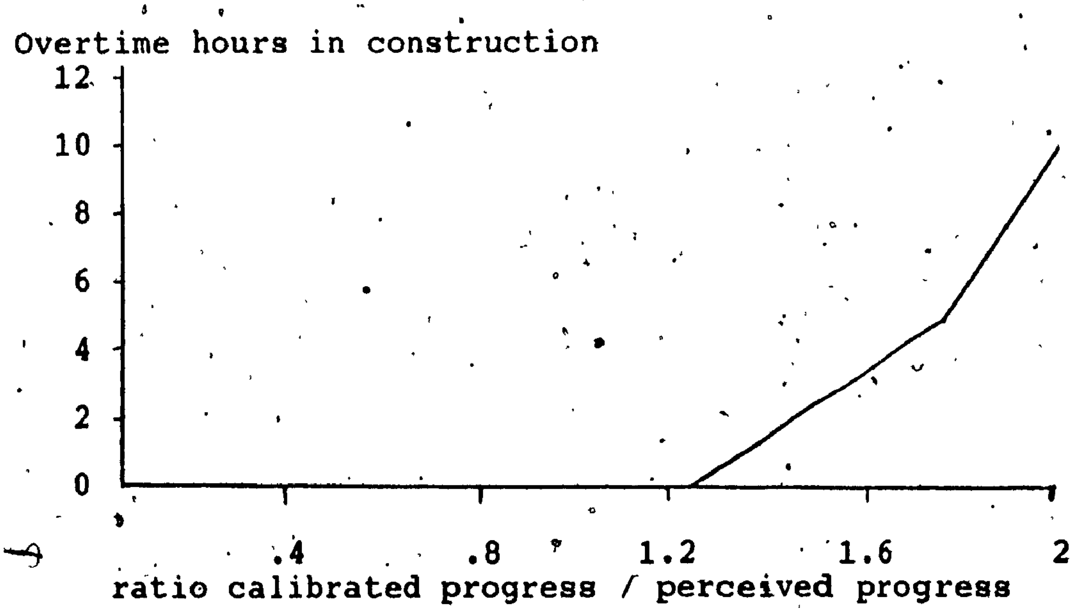


figure 50. Overtime hours in construction

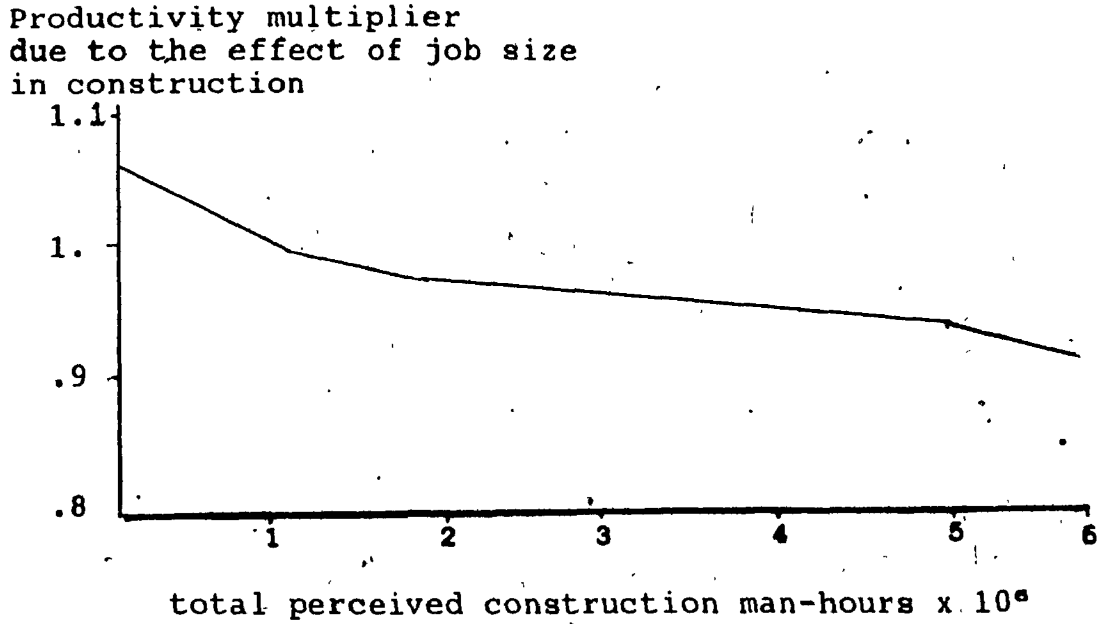


figure 51. Productivity multiplier due to the effect of job size in construction

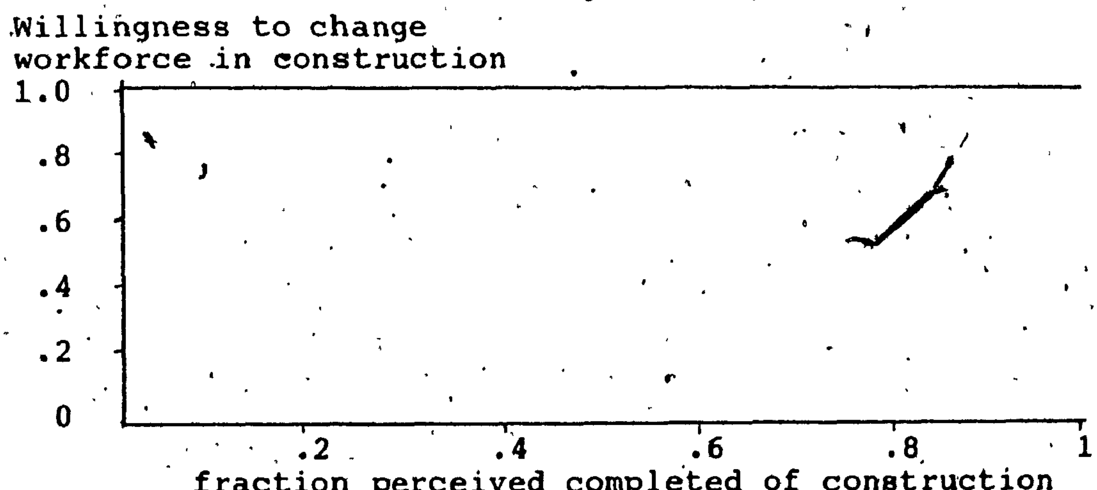


figure 52. Willingness to change workforce in construction

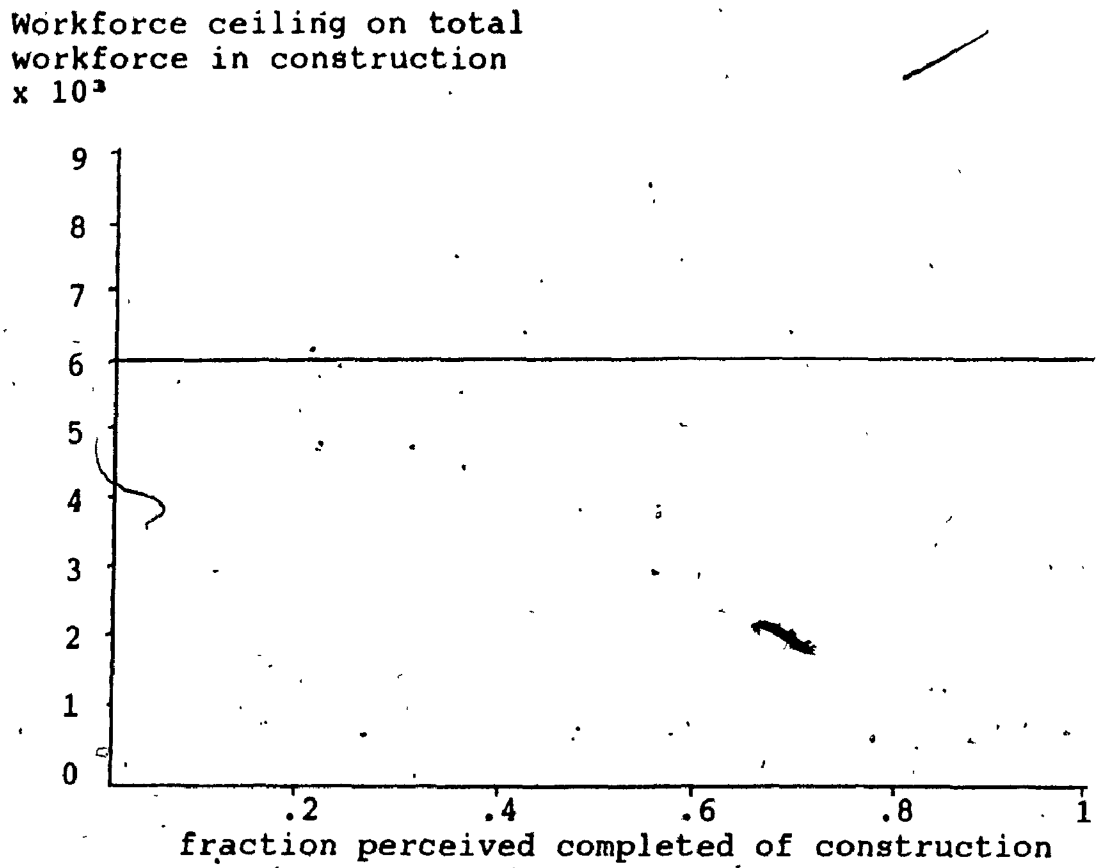


figure 55. Ceiling on total workforce in construction

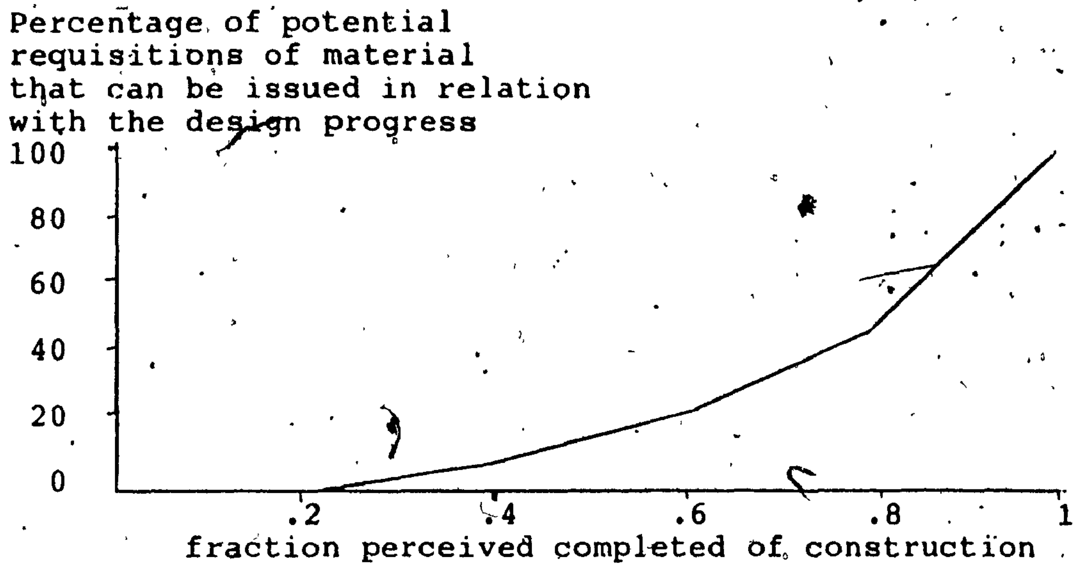


figure 56. Potential quantity of requisitions that can be issued in relation with the design progress

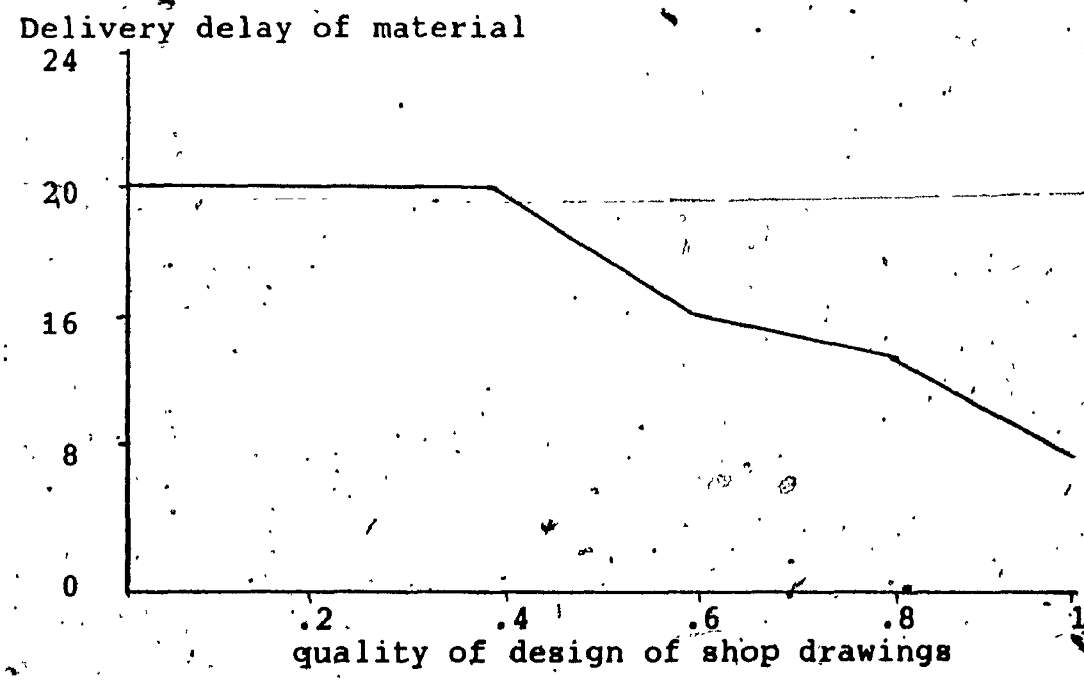


figure 57. Delivery delay of material

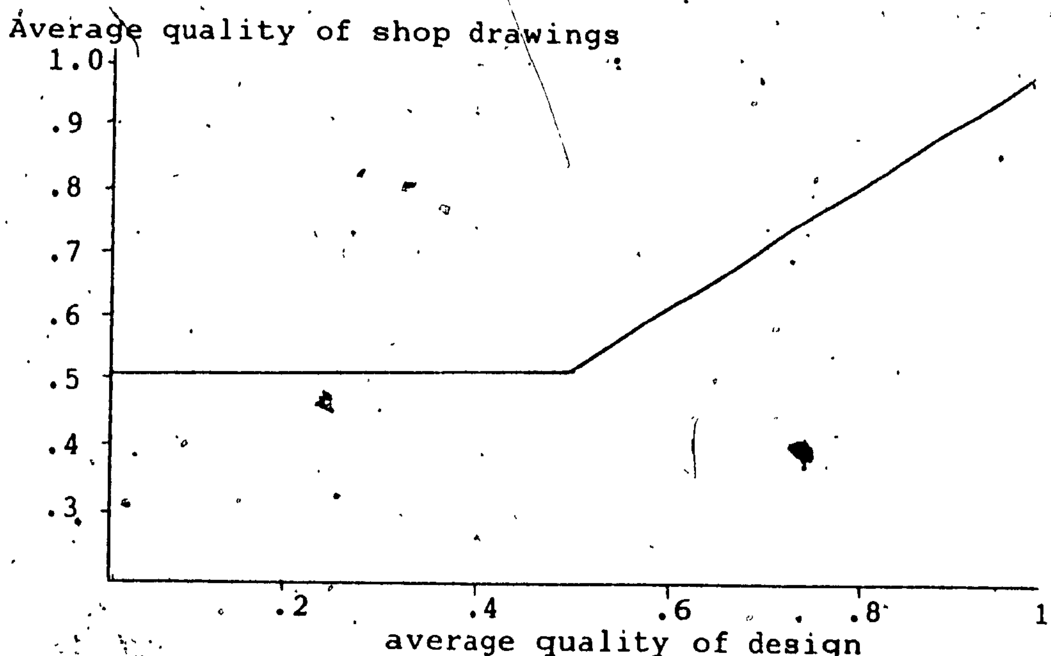


figure 58. Average quality of shop drawings

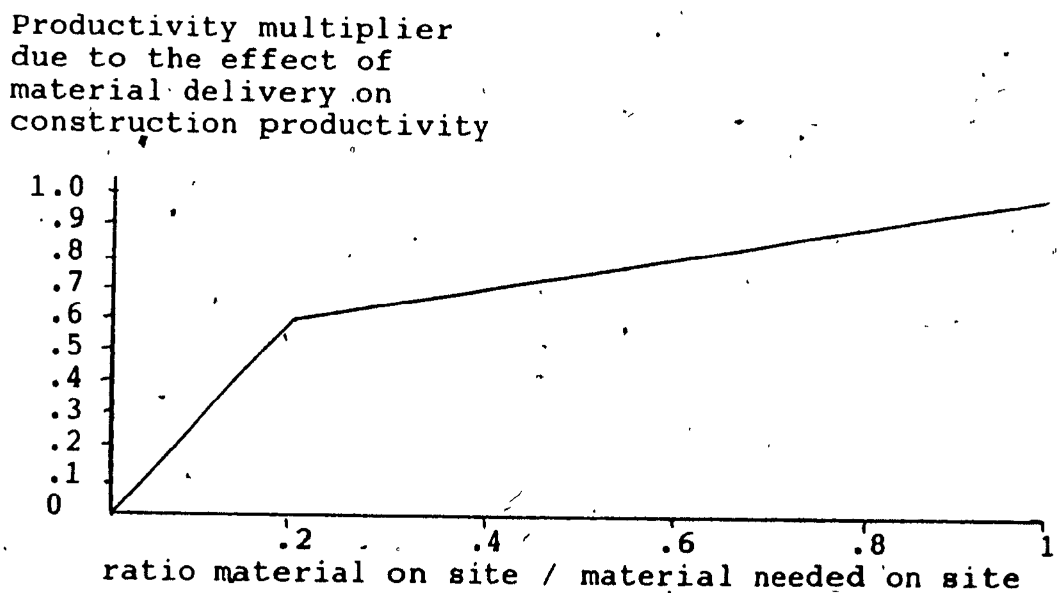


figure 59. Effect of delivered material on construction productivity

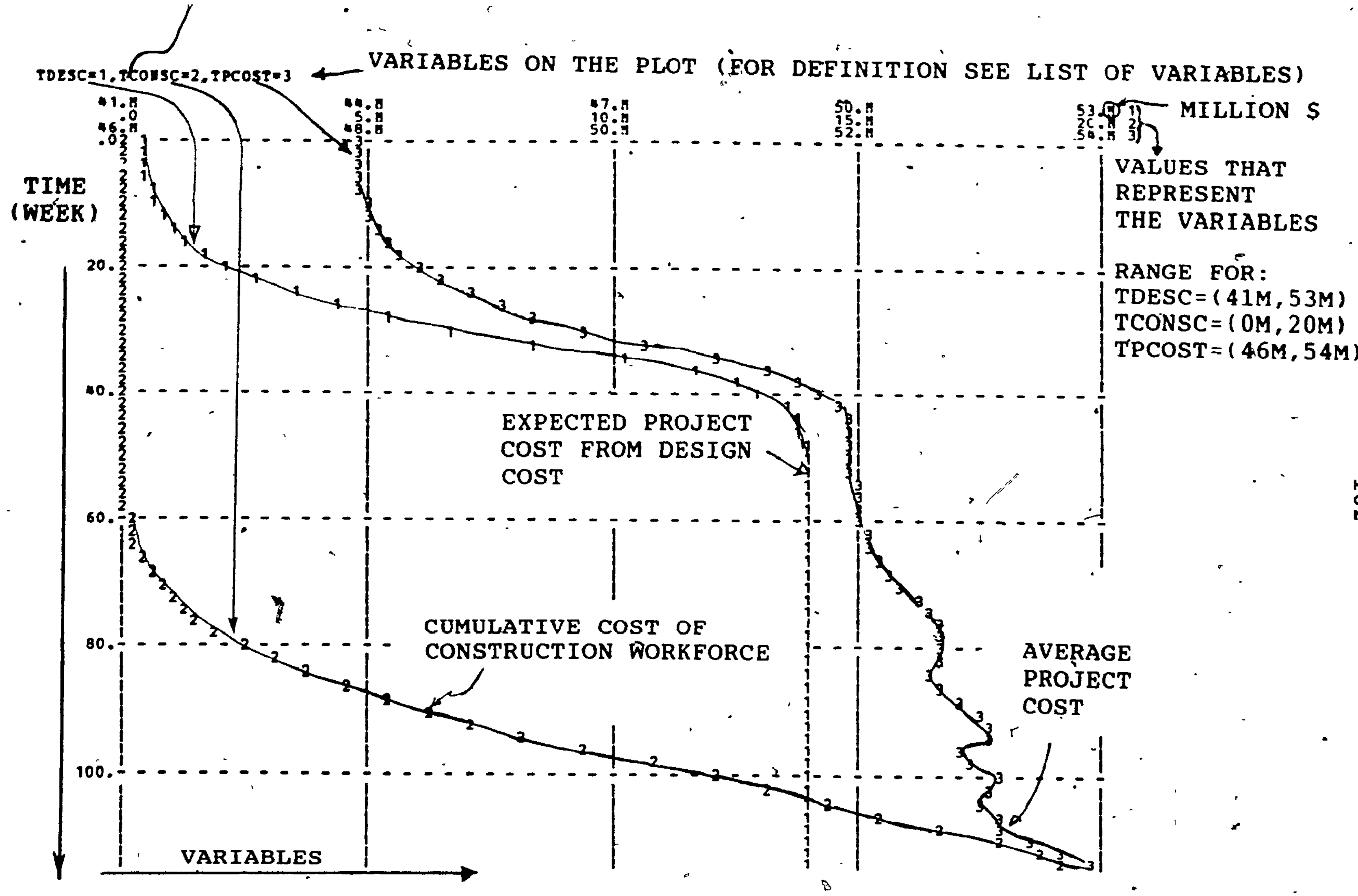


figure 60. Conventional project; run B

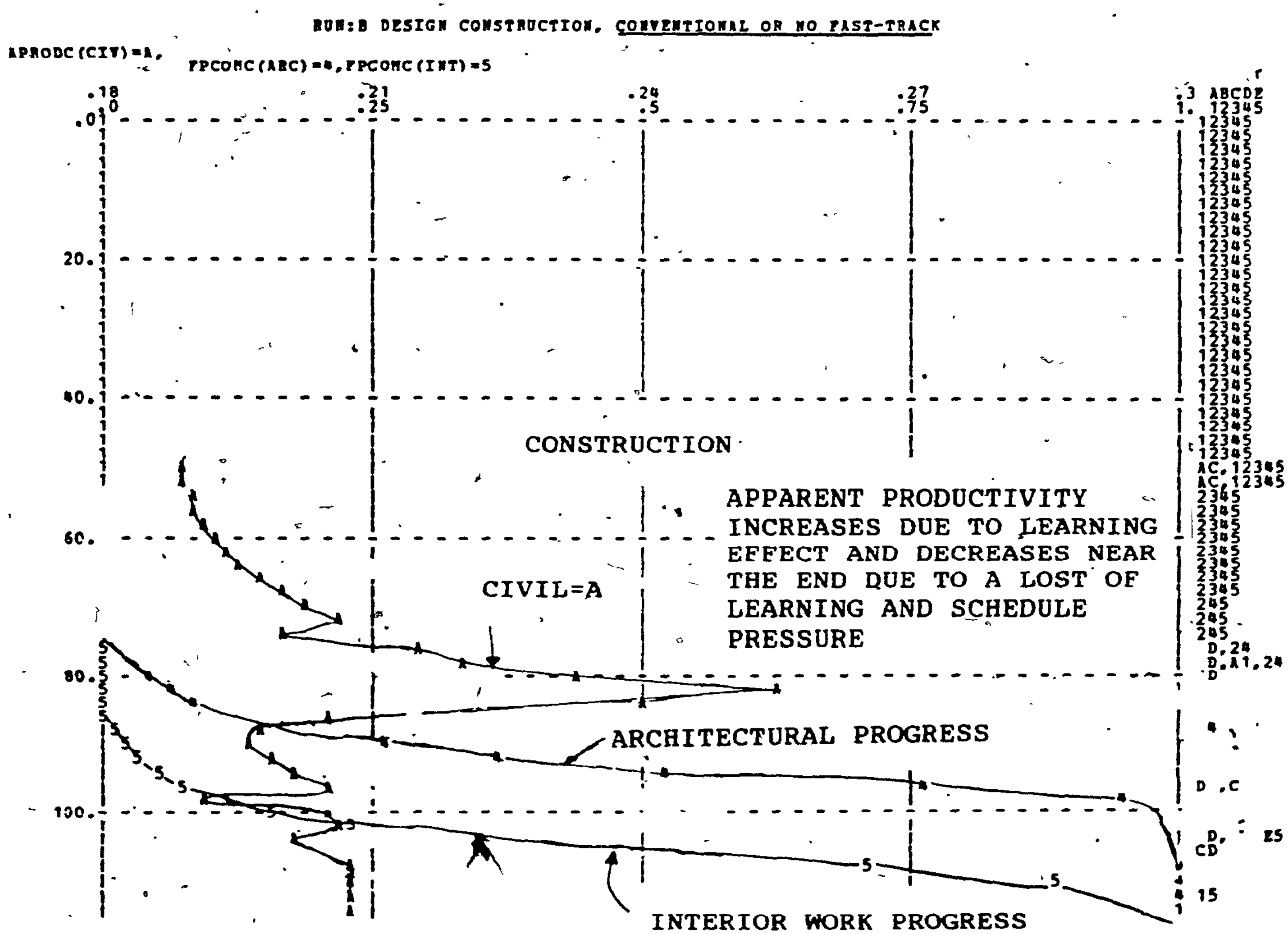


figure 61. Conventional project; run B

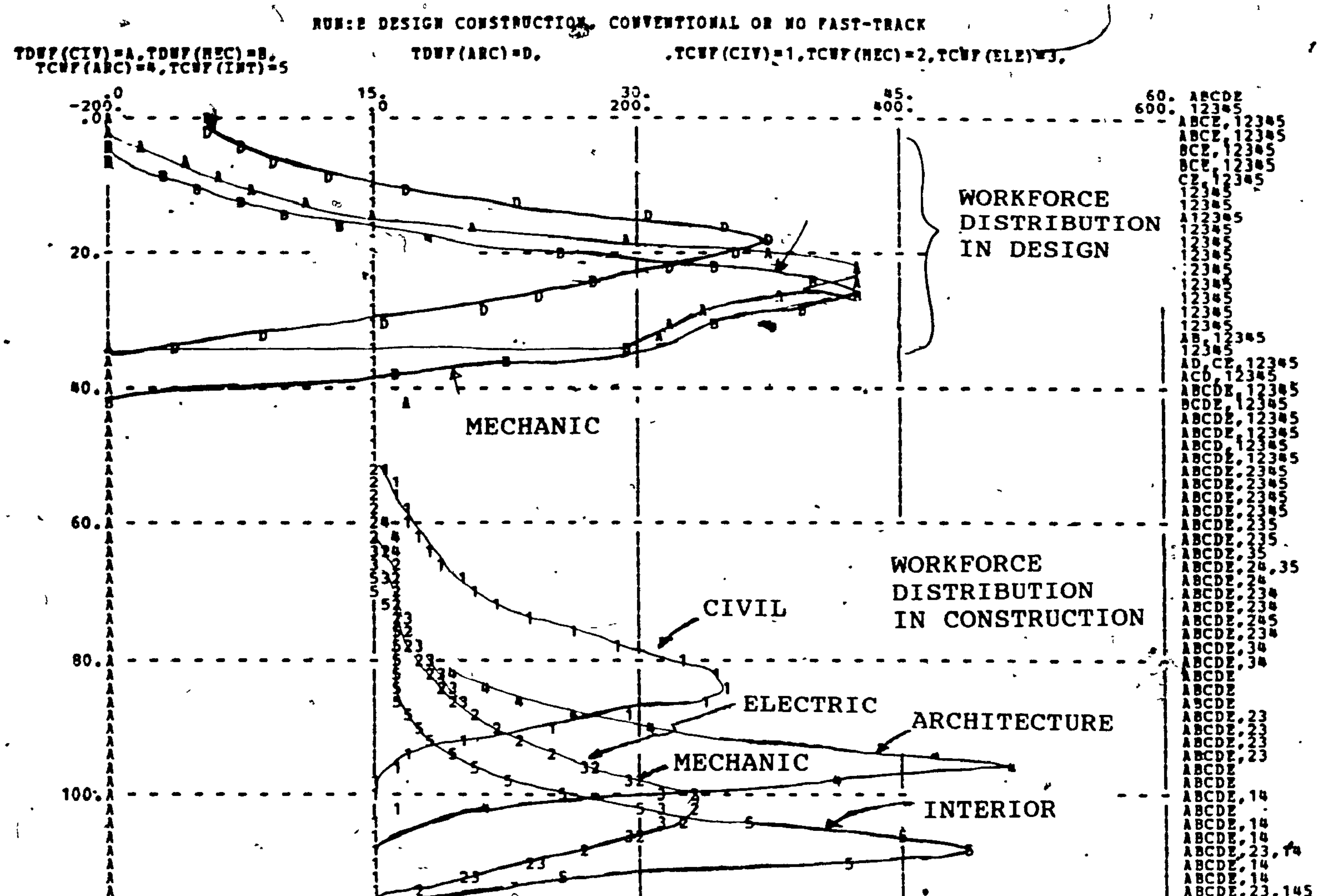


figure 62. Conventional project; run B

RUN:B DESIGN CONSTRUCTION, CONVENTIONAL OR NO FAST-TRACK

FPCONC(CIV)=A, FPCONC(MEC)=B, FPCONC(ELE)=C, FPCONC(ARC)=D, FPCONC(INT)=E, MTLOST(CIV)=1, MTLOST(MEC)=2, MTLOST(ELE)=3, MTLOST(ARC)=4, MTLOST(INT)=5

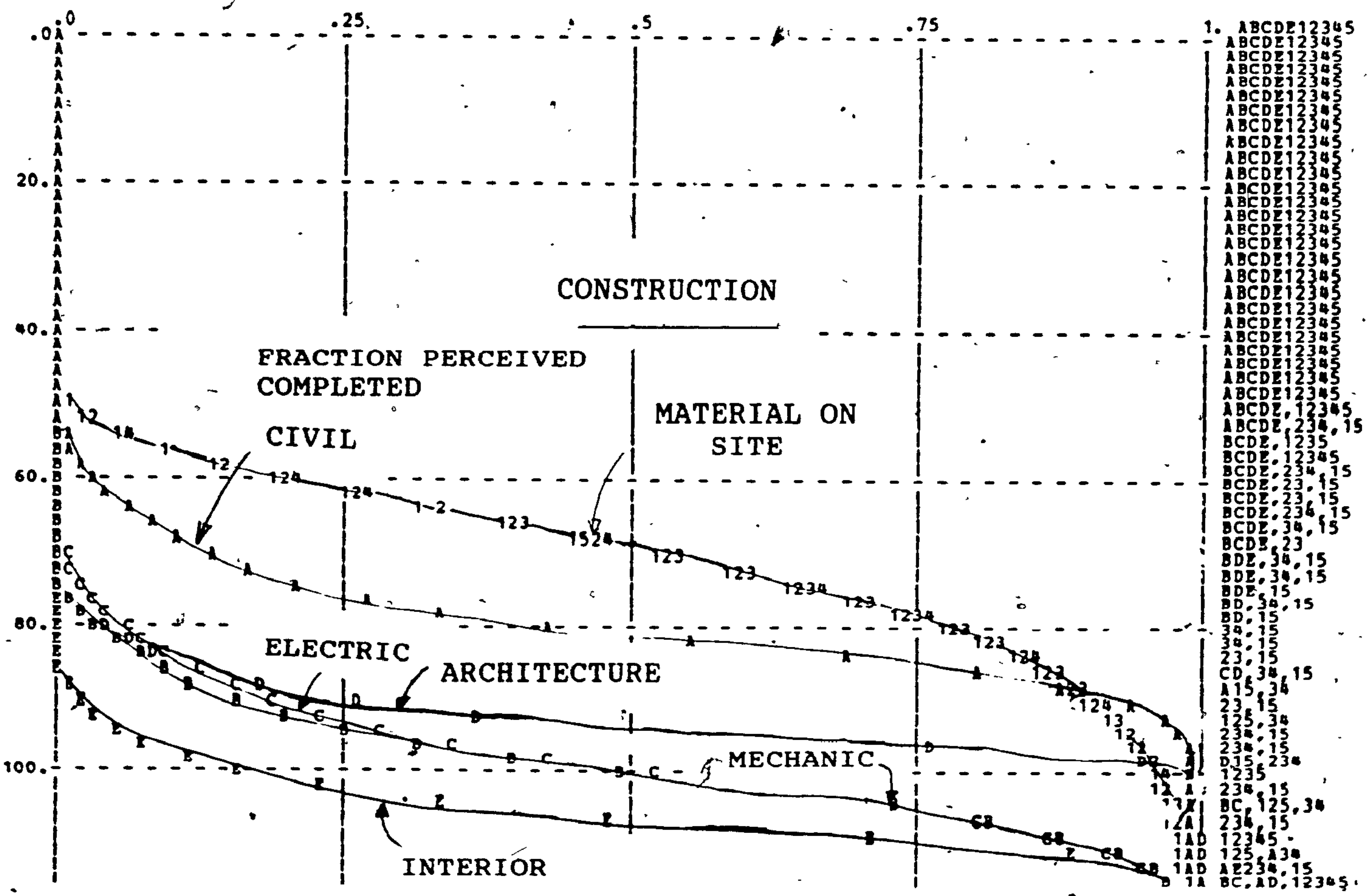


figure 63. Conventional project; run B

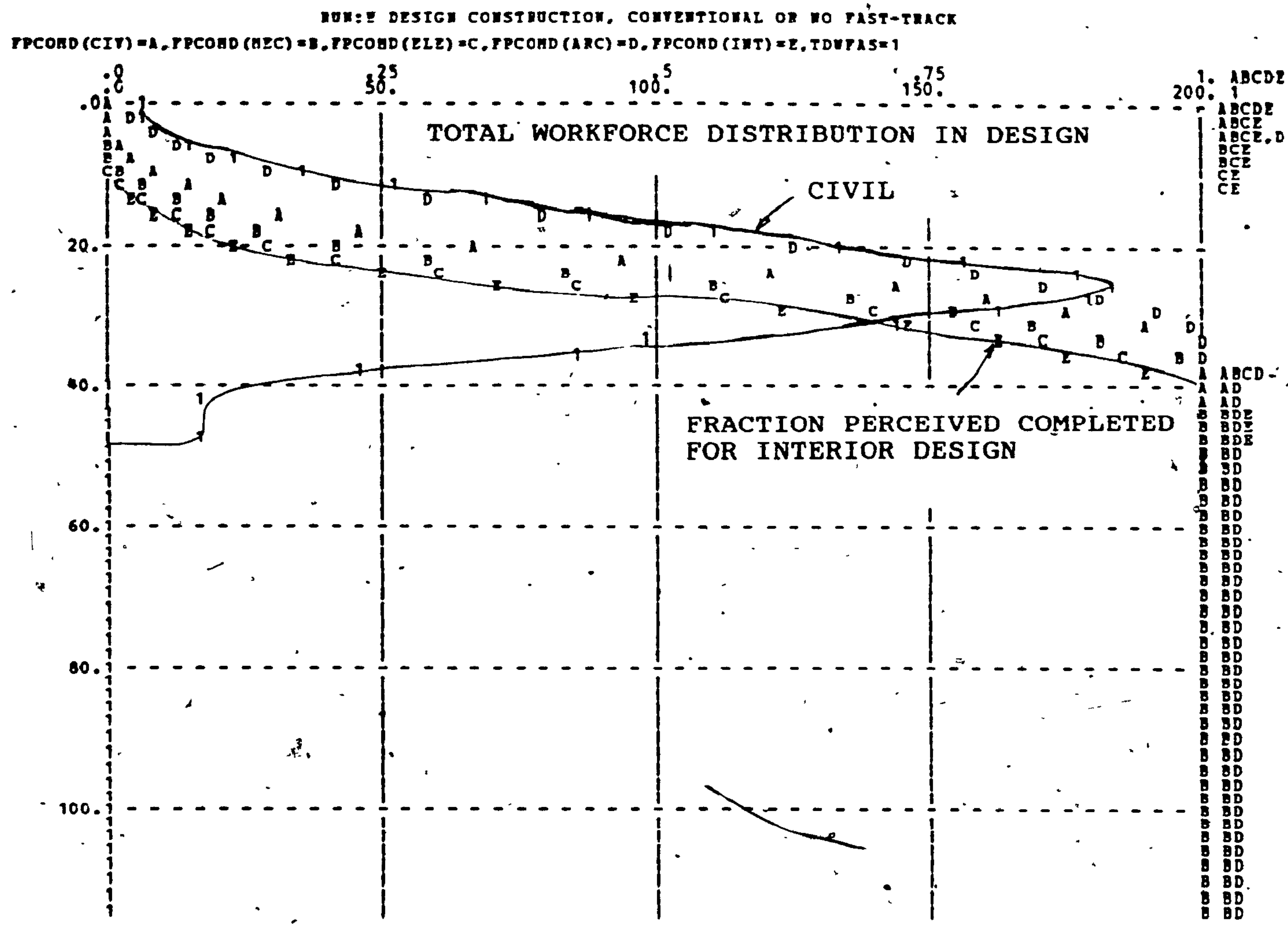


figure 64. Conventional project; run B

RUN:B DESIGN CONSTRUCTION, CONVENTIONAL OR NO FAST-TRACK

LEPROC(CIV)=1,LEPROC(MEC)=2,LEPROC(ELE)=3,LEPROC(ARC)=4,LEPROC(INT)=5

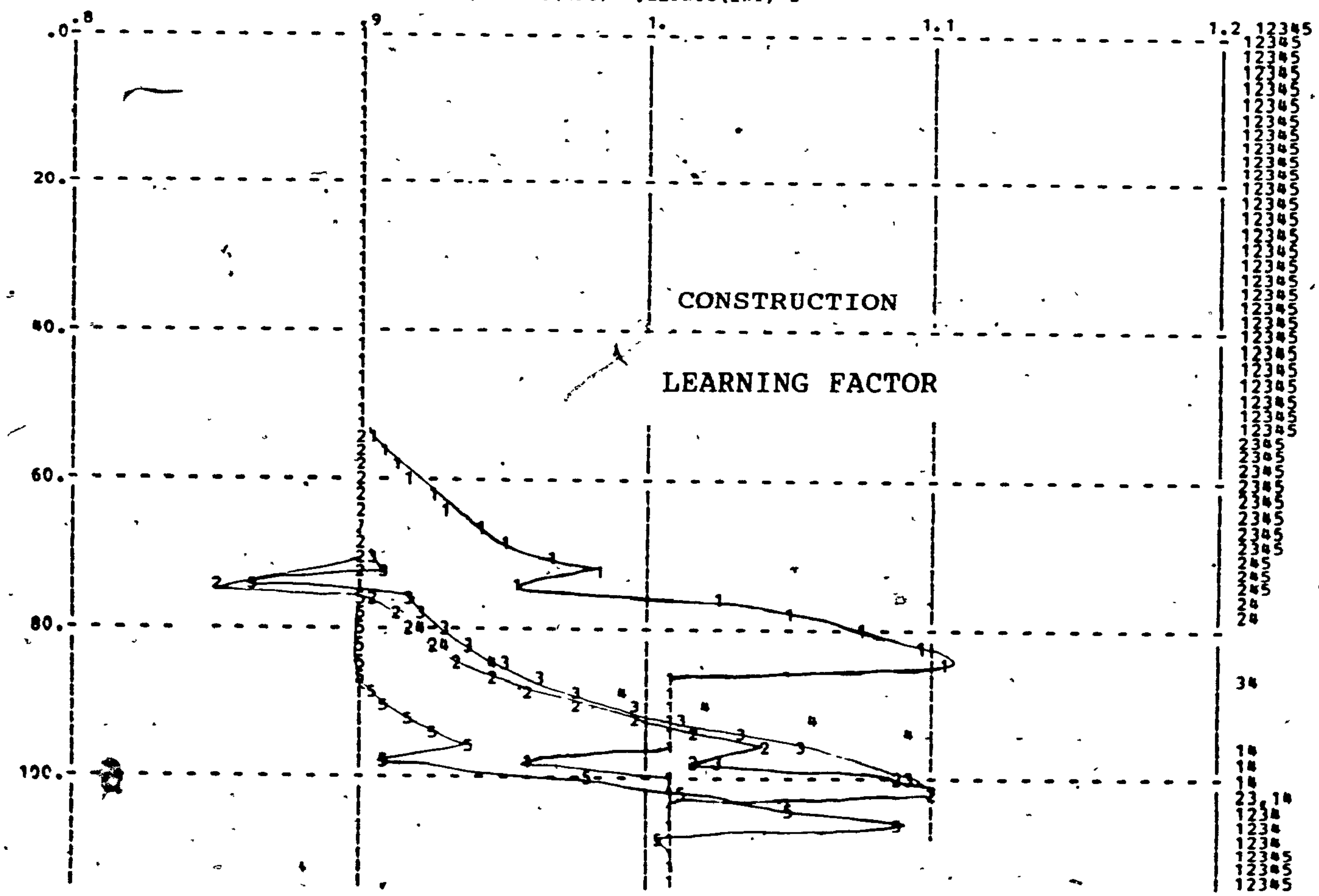


figure 65. Conventional project; run B

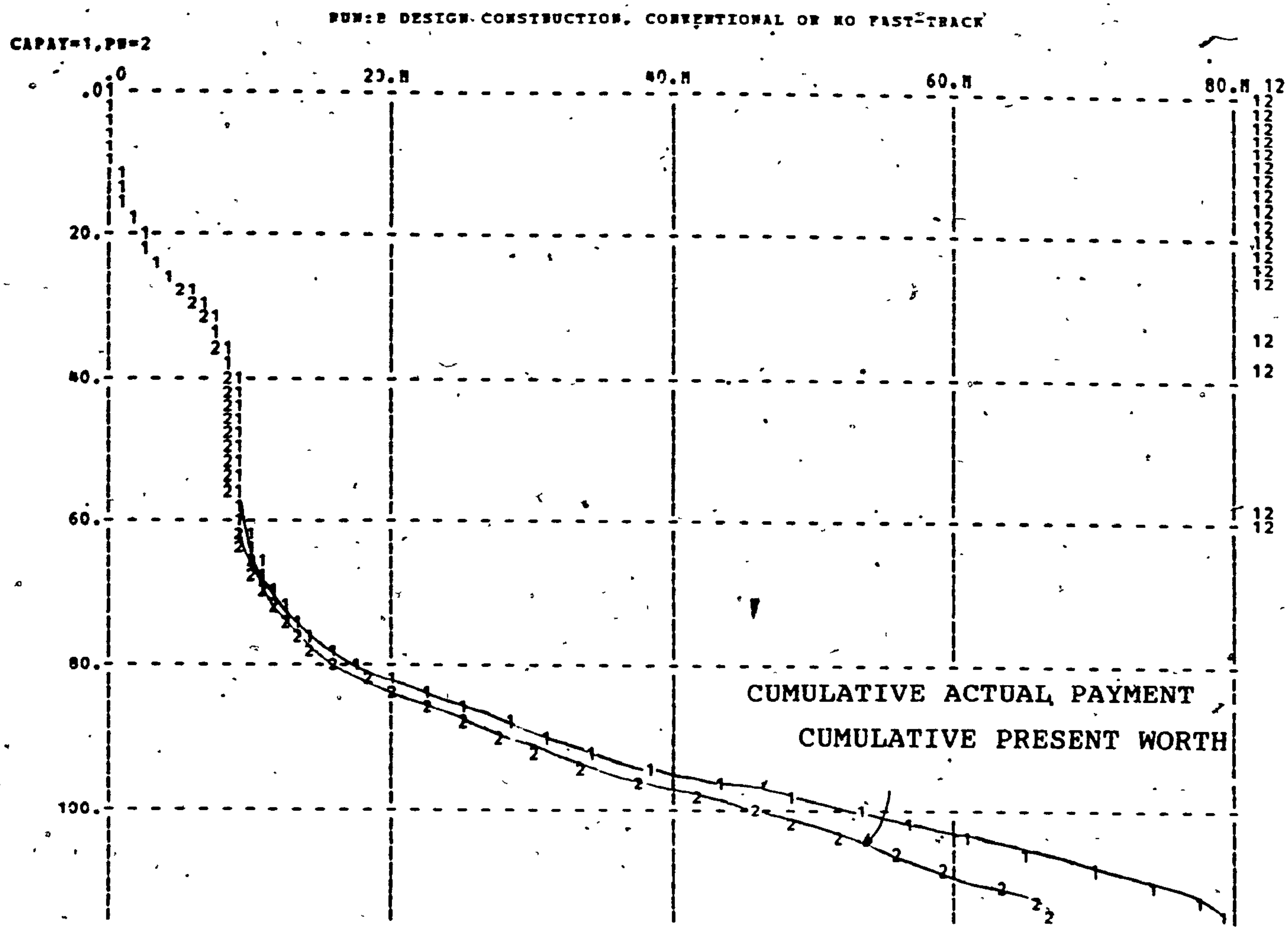


figure 66. Conventional project; run B

RUN:B DESIGN CONSTRUCTION, CONVENTIONAL OR NO FAST-TRACK

SCDC(CIV)=A,SCDC(MEC)=B,SCDC(ELE)=C,SCDC(ARC)=D,SCDC(INT)=E,TCWPAS=1

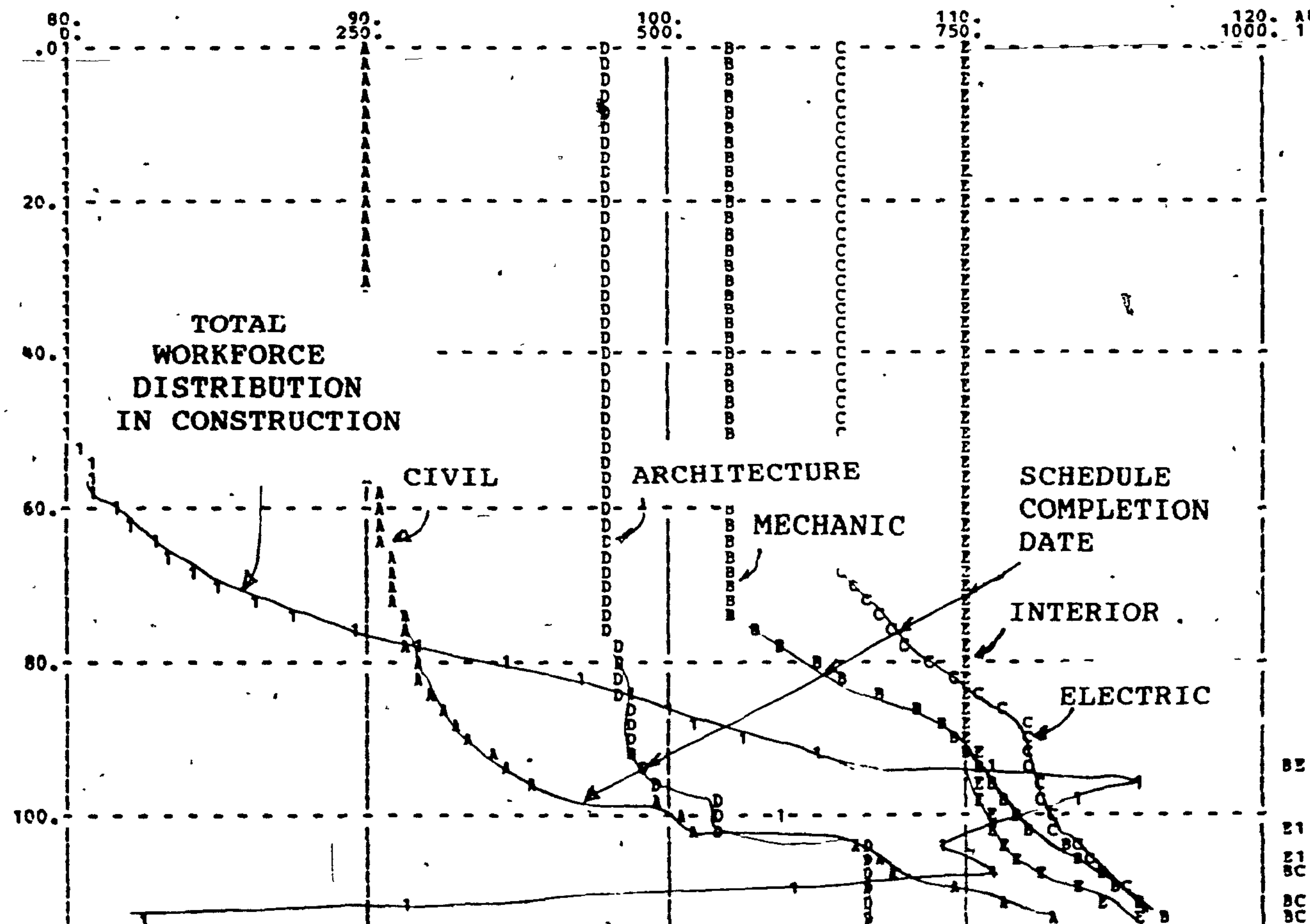


figure 67. Conventional project; run B

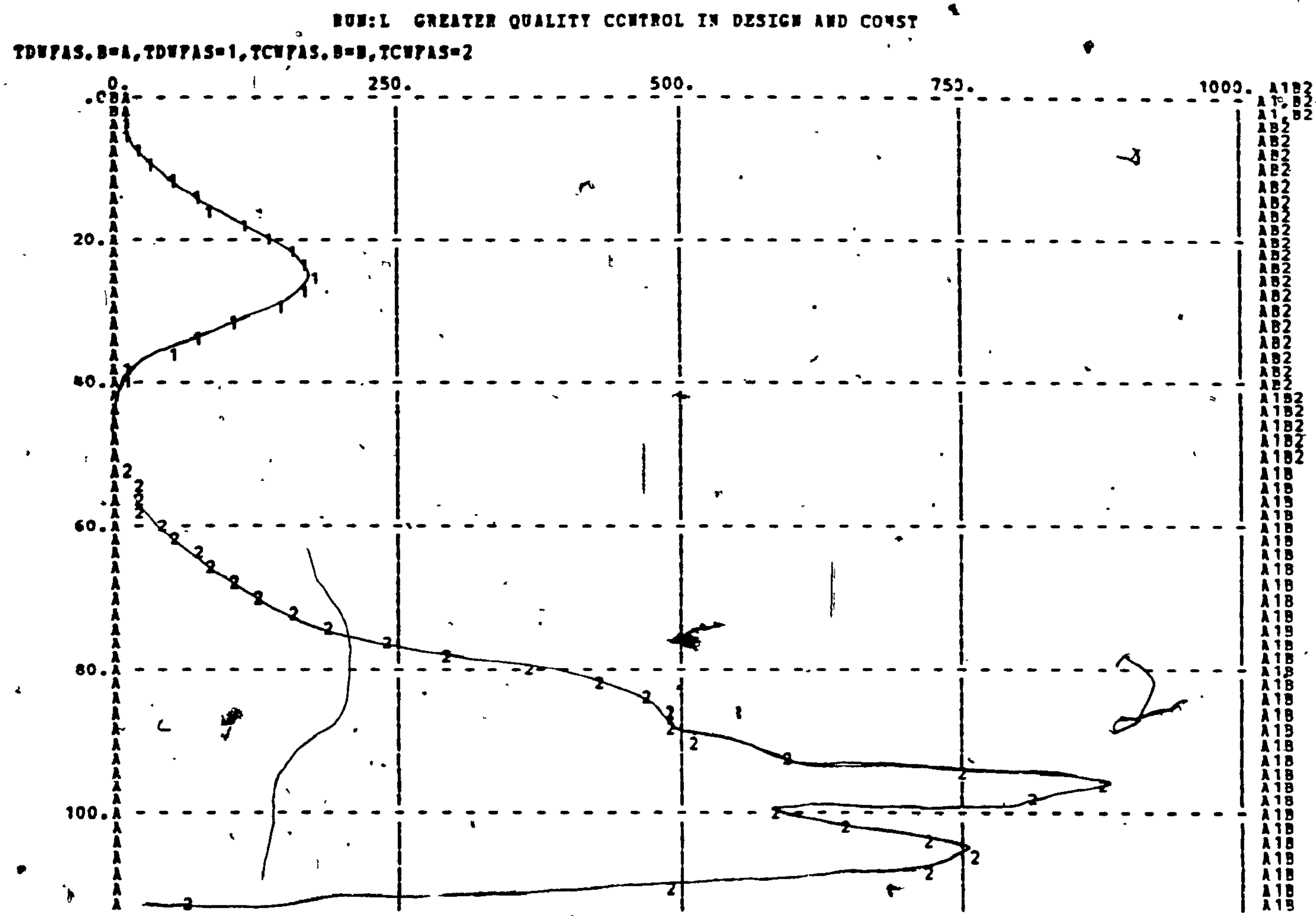


figure 68. Conventional project; run L
quality (QC and QD) modified

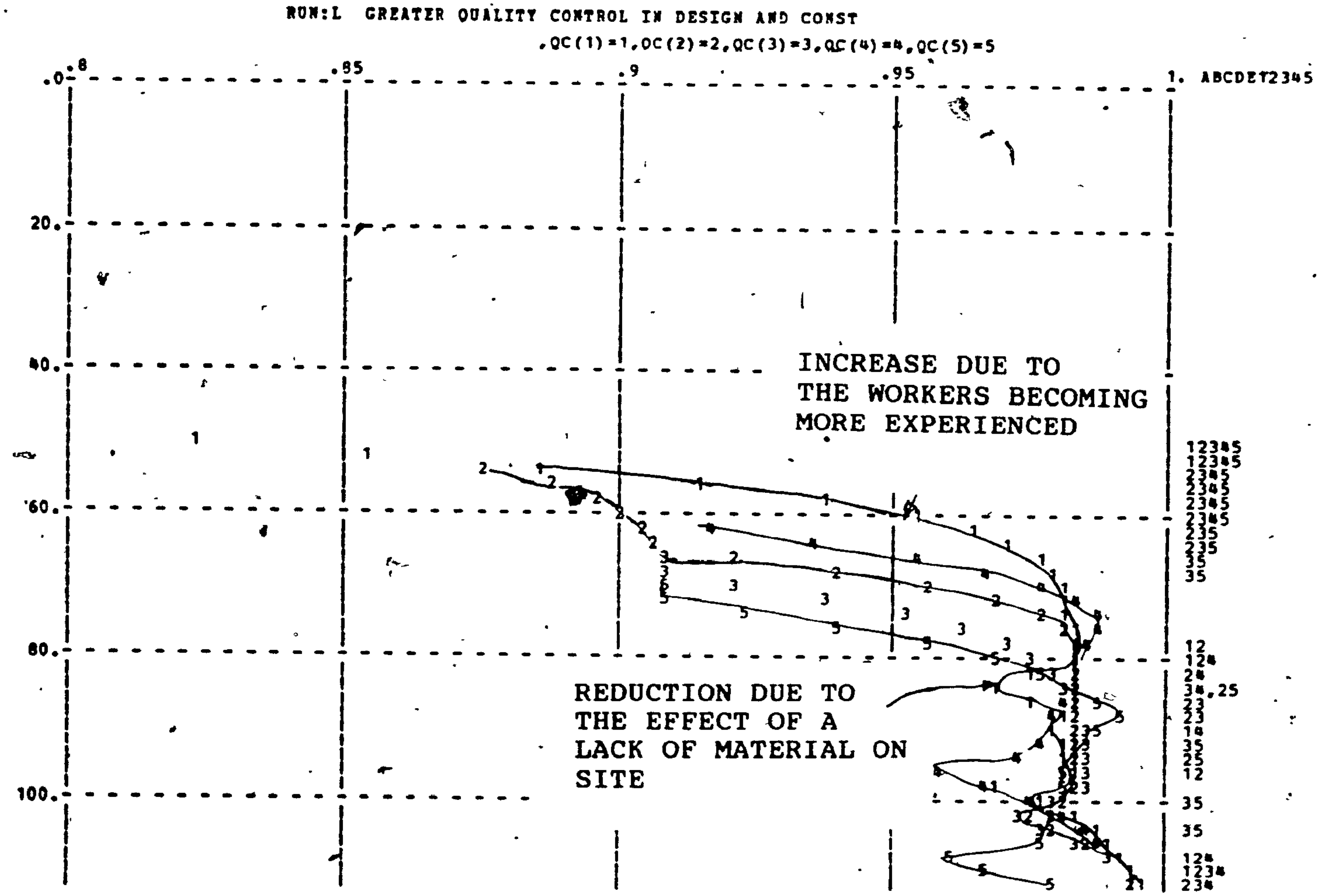


figure 69. Conventional project; run L quality (QC and QD) modified

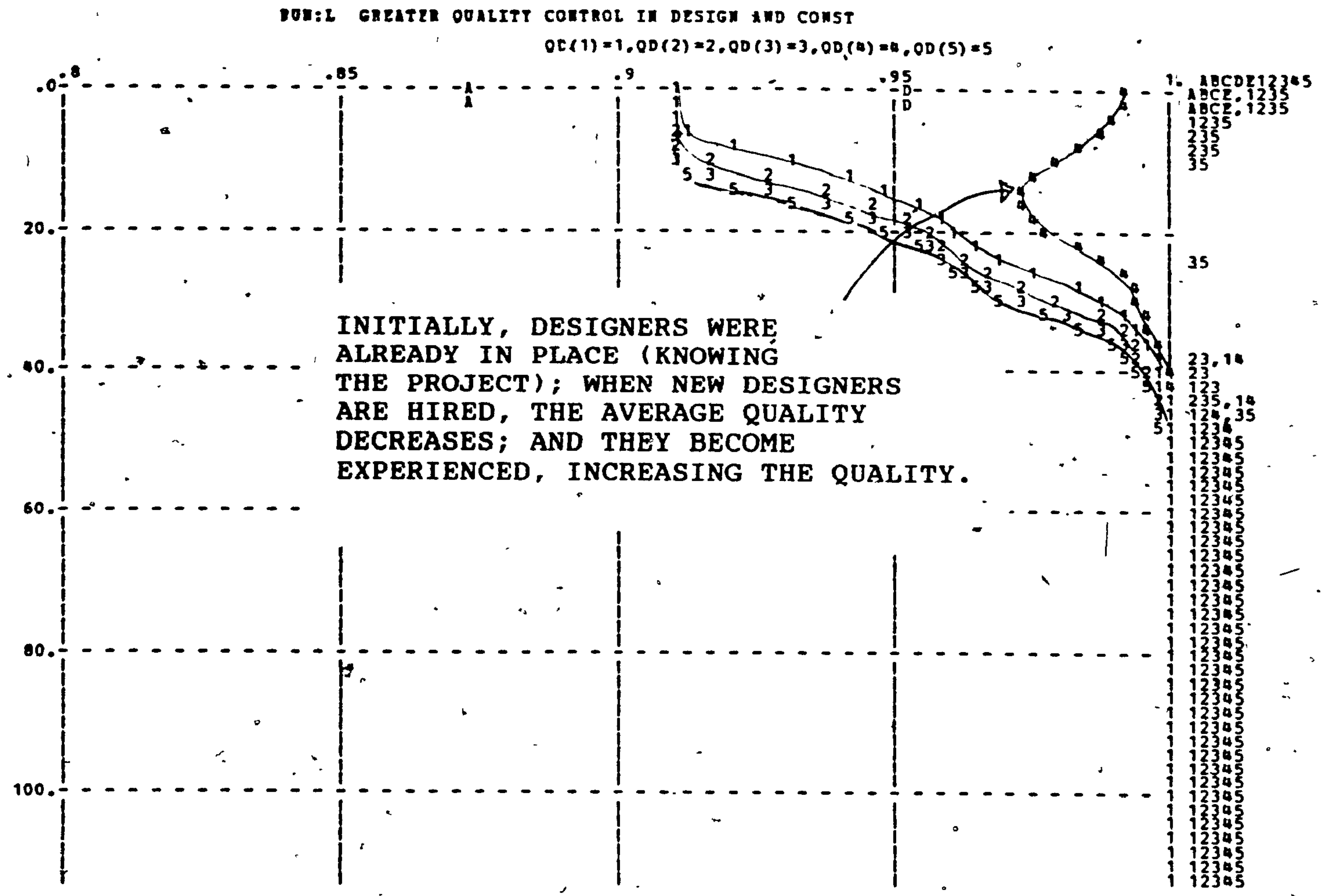


figure 70. Conventional project; run L quality (QC and QD) modified

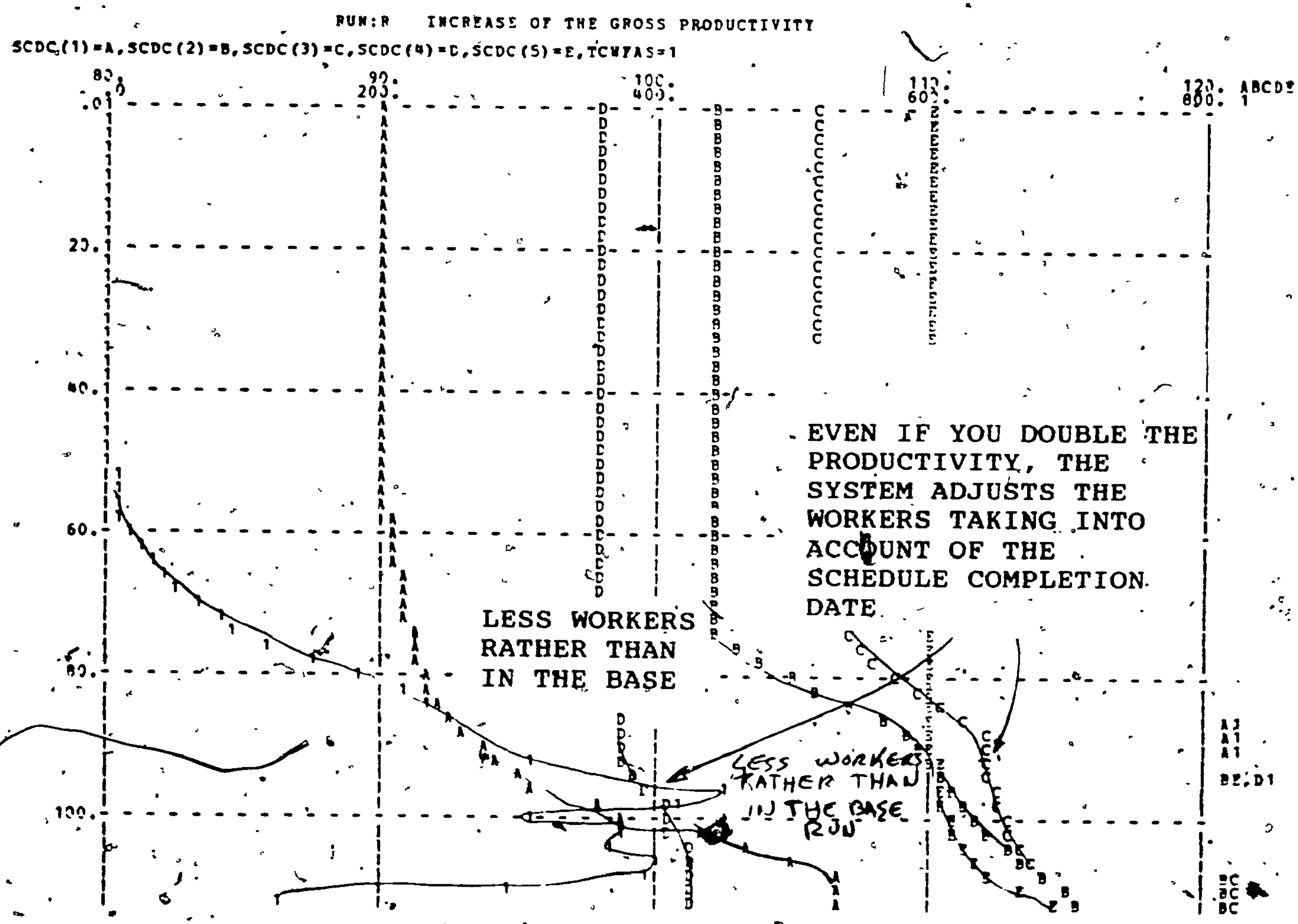


figure 71. Conventional project (Run R); gross productivity increased

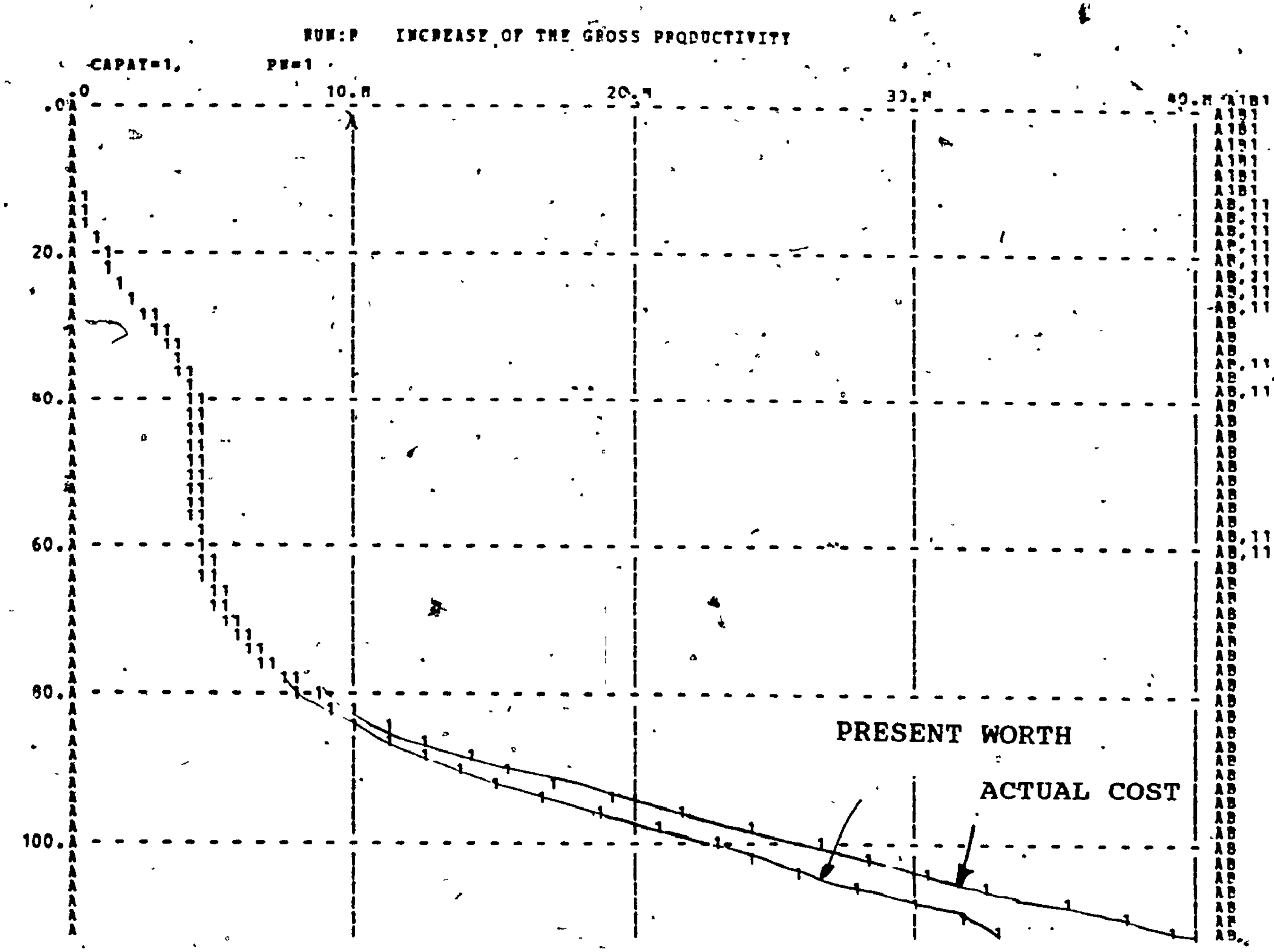


figure 72. Conventional project (Run R); gross productivity increased

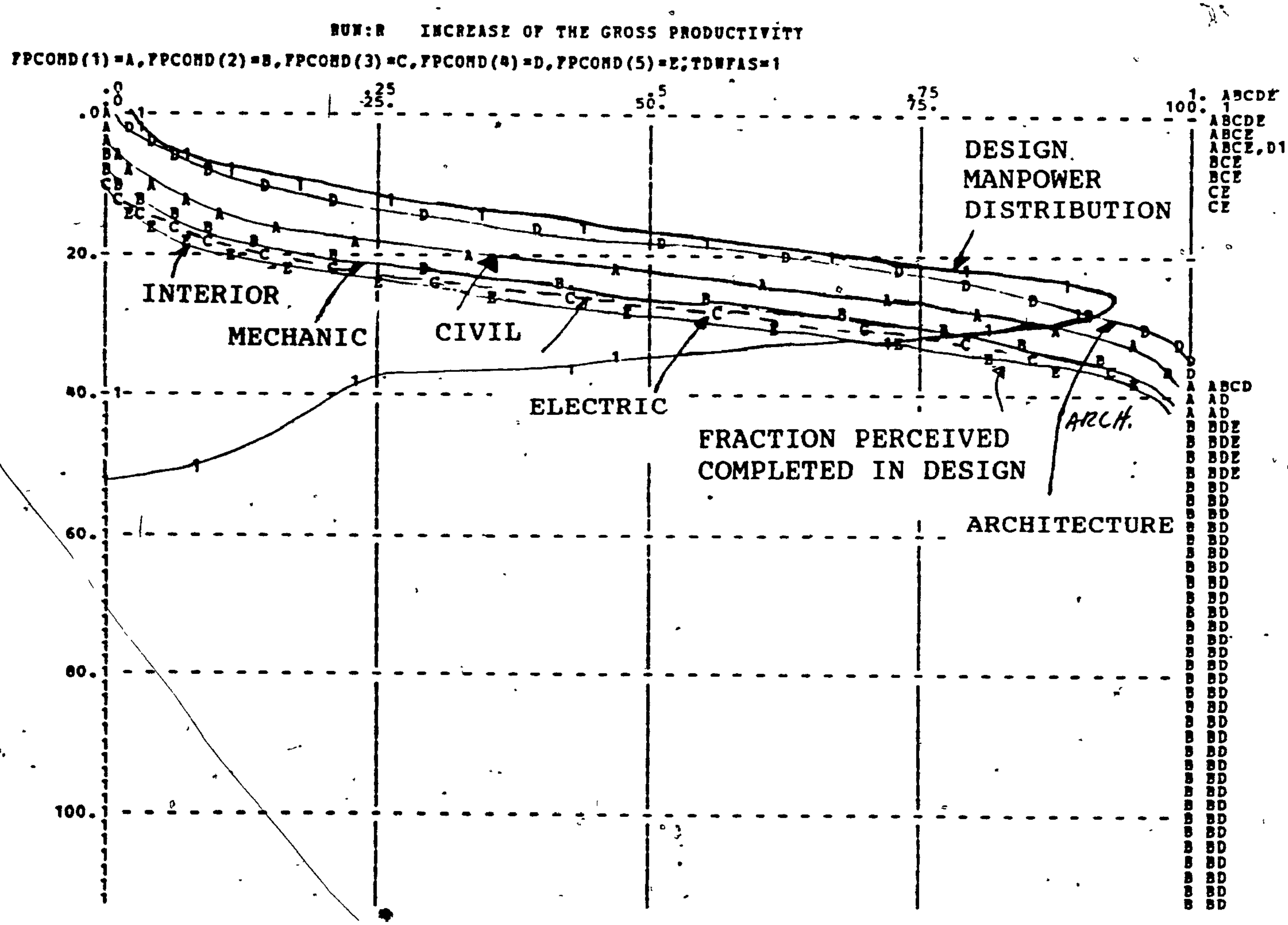


figure 73. Conventional project (Run R); gross productivity increased

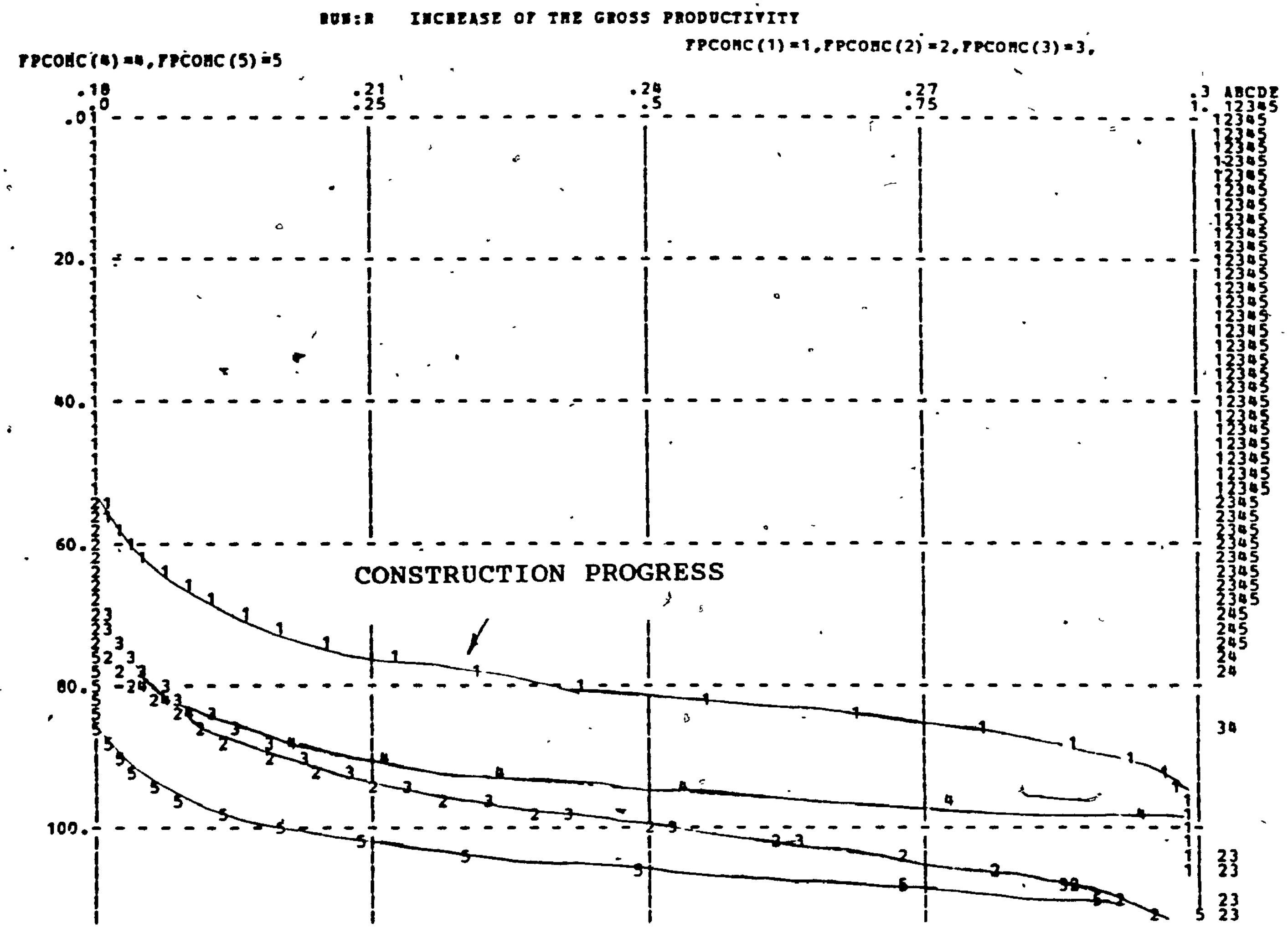


figure 74. Conventional project (Run R); gross productivity increased

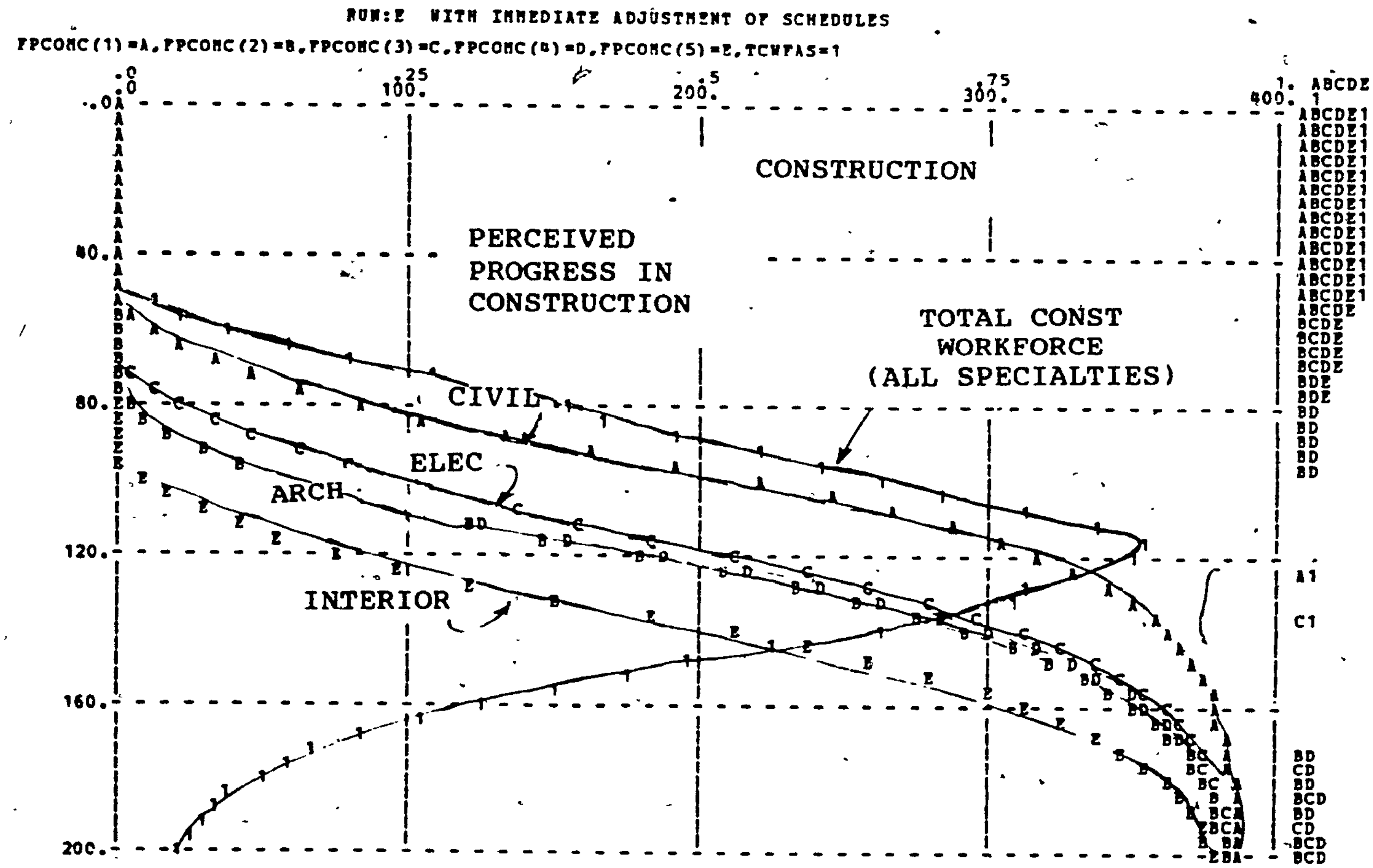


figure 75. Conventional project (Run E); immediate adjustment of the schedules

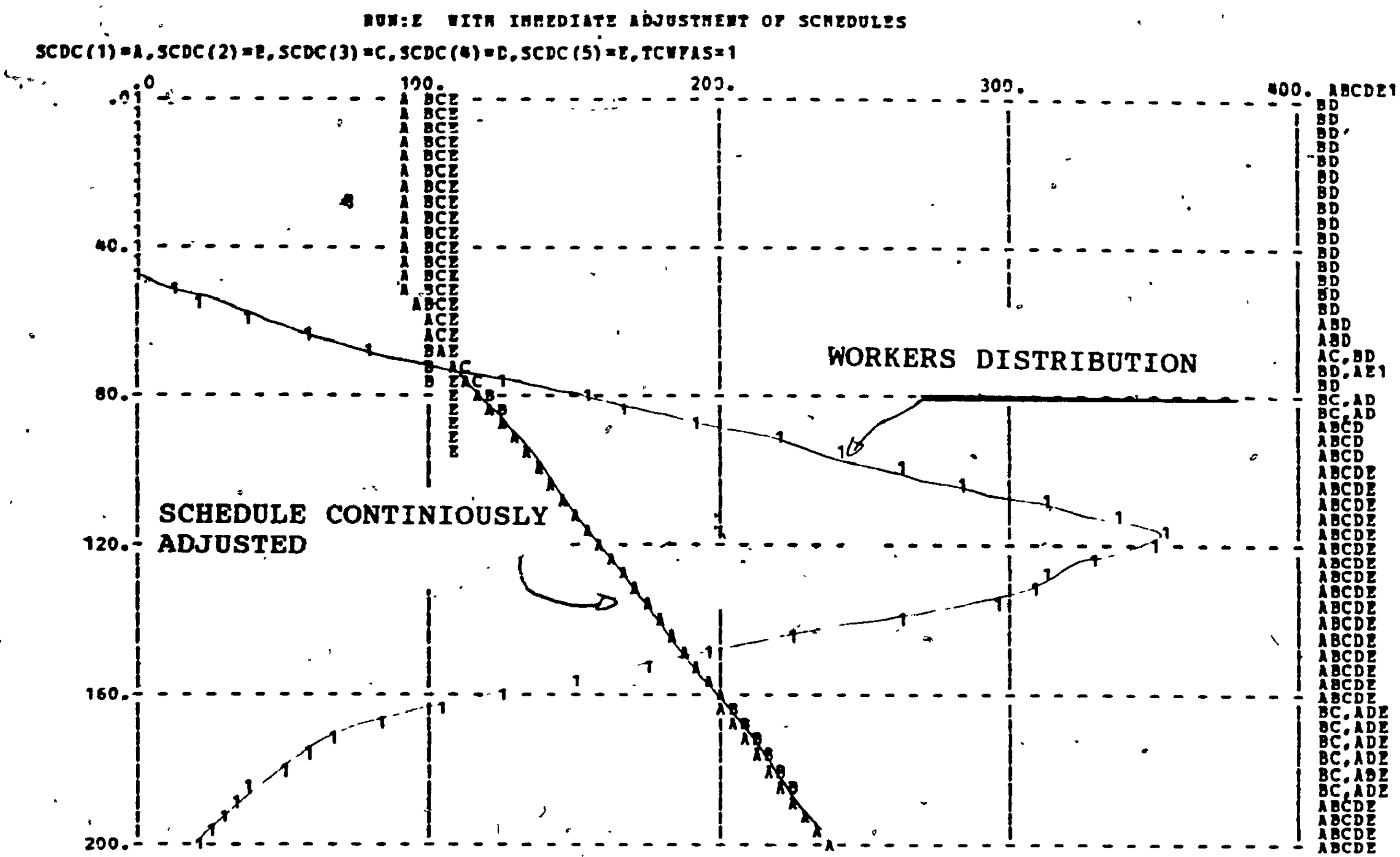


figure 76. Conventional project (Run E); immediate adjustment of the schedules

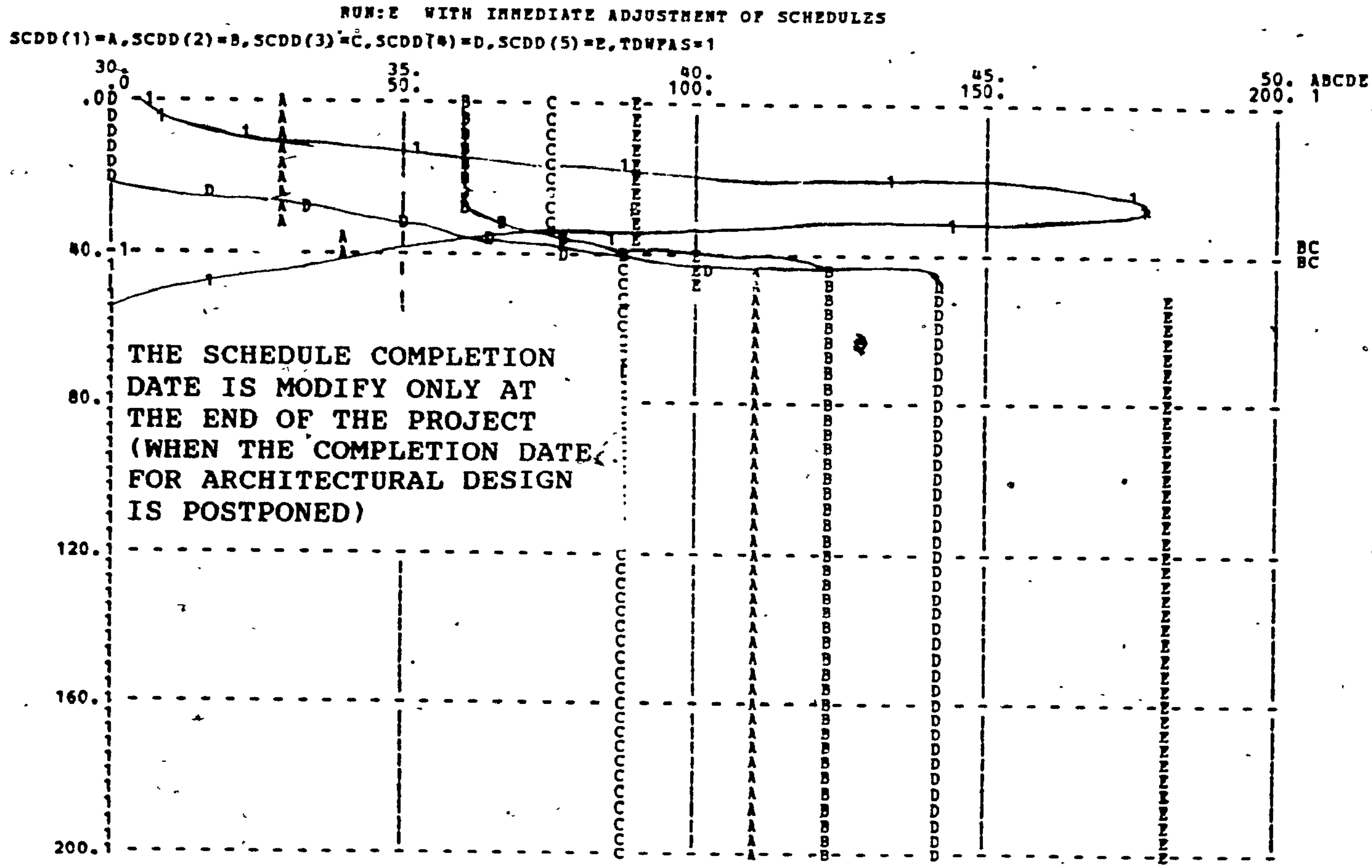


figure 77. Conventional project (Run E);
immediate adjustment of the schedules

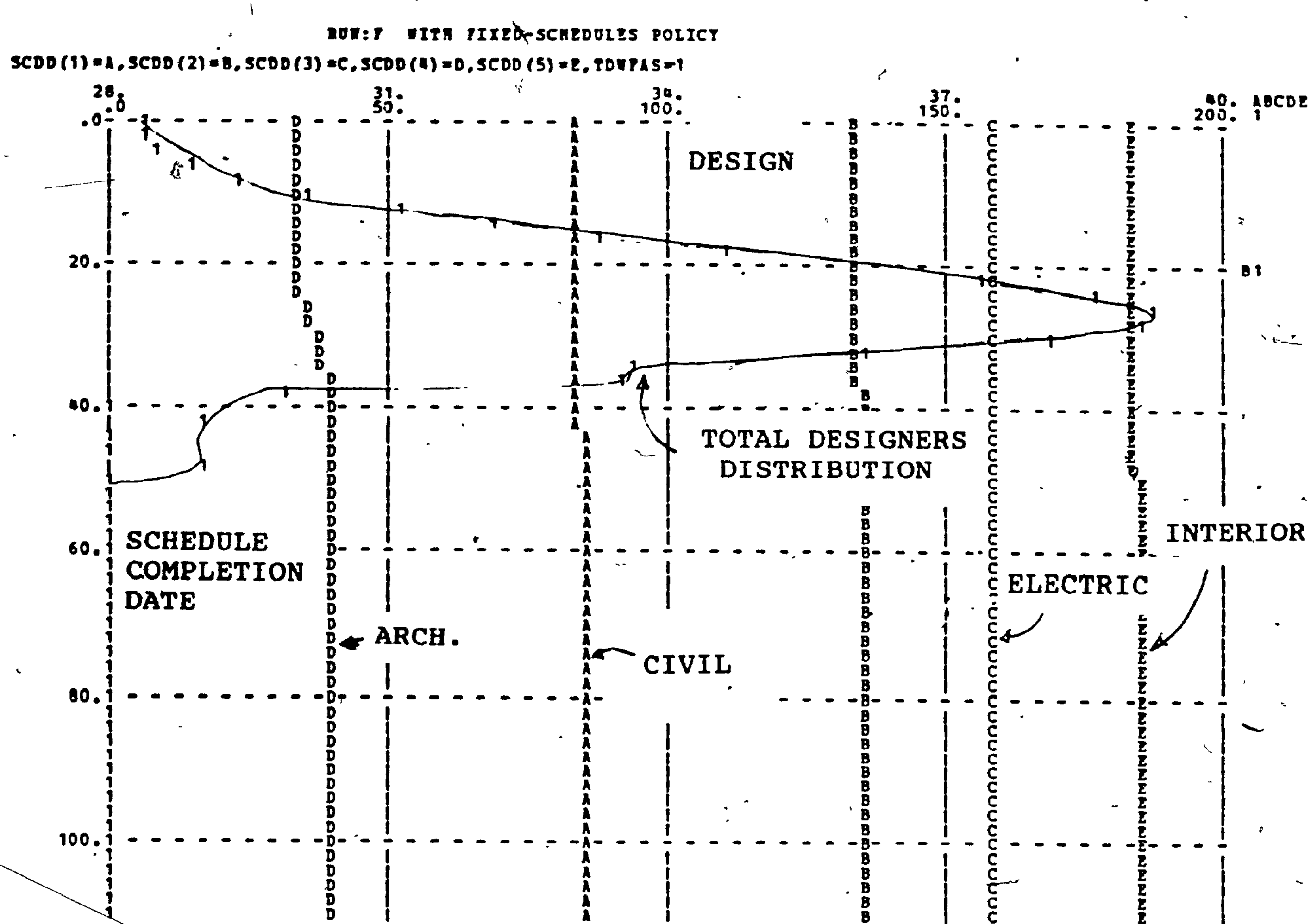


figure 78. Conventional project (Run F): fixed construction schedule

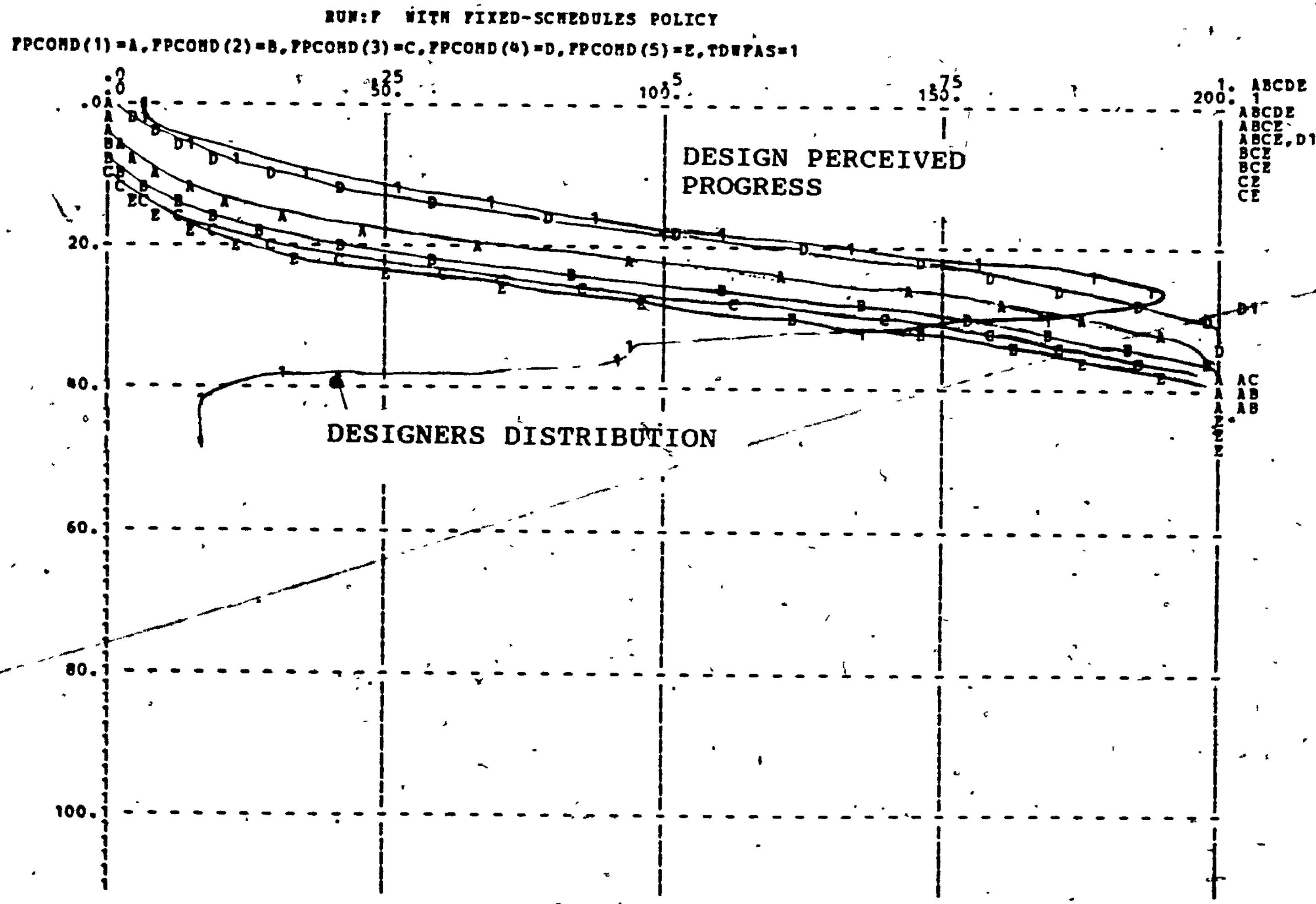


figure 79. Conventional project (Run F); fixed construction schedule

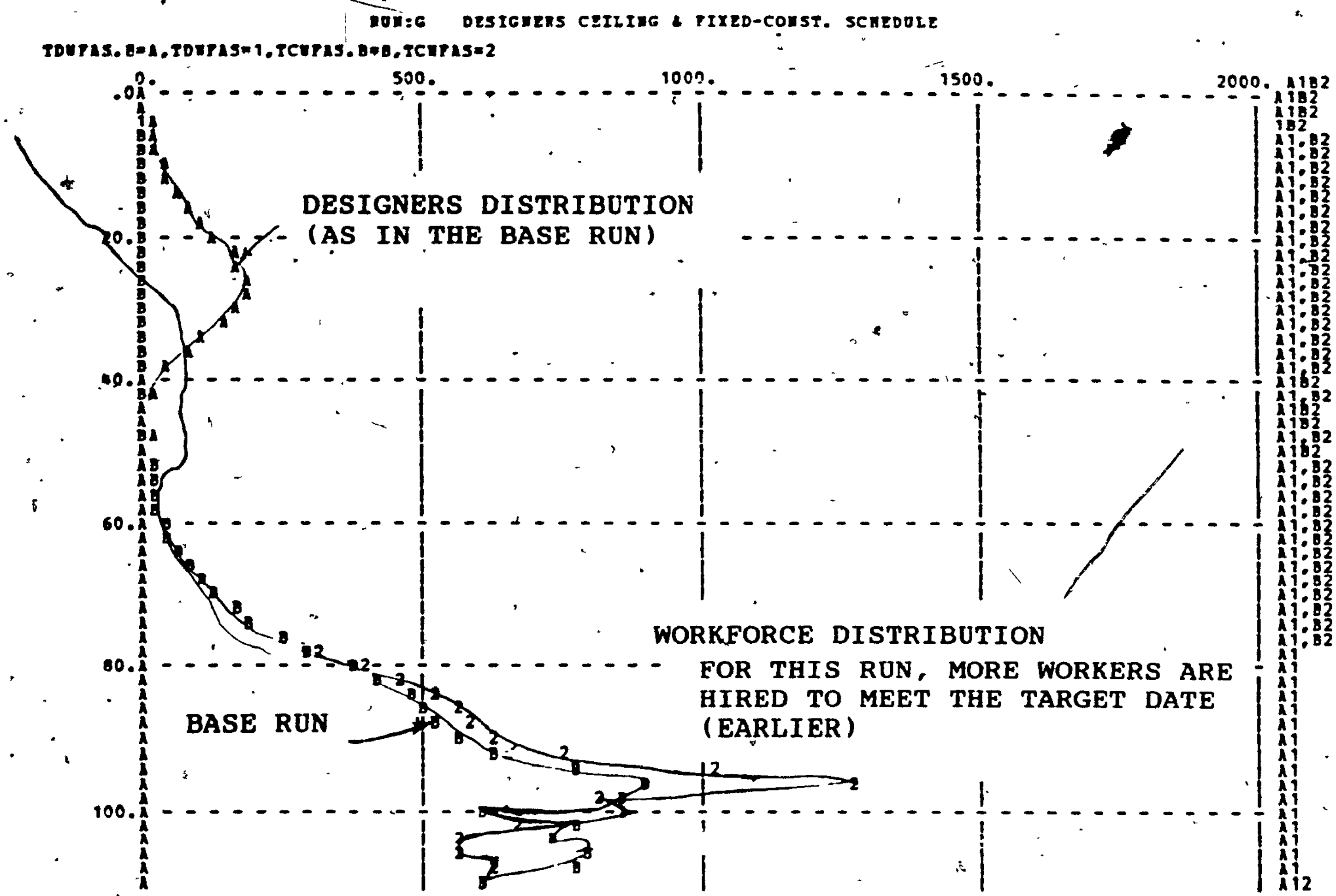


figure 80. Conventional project (Run G); fixed construction schedule and a ceiling on designer workforce

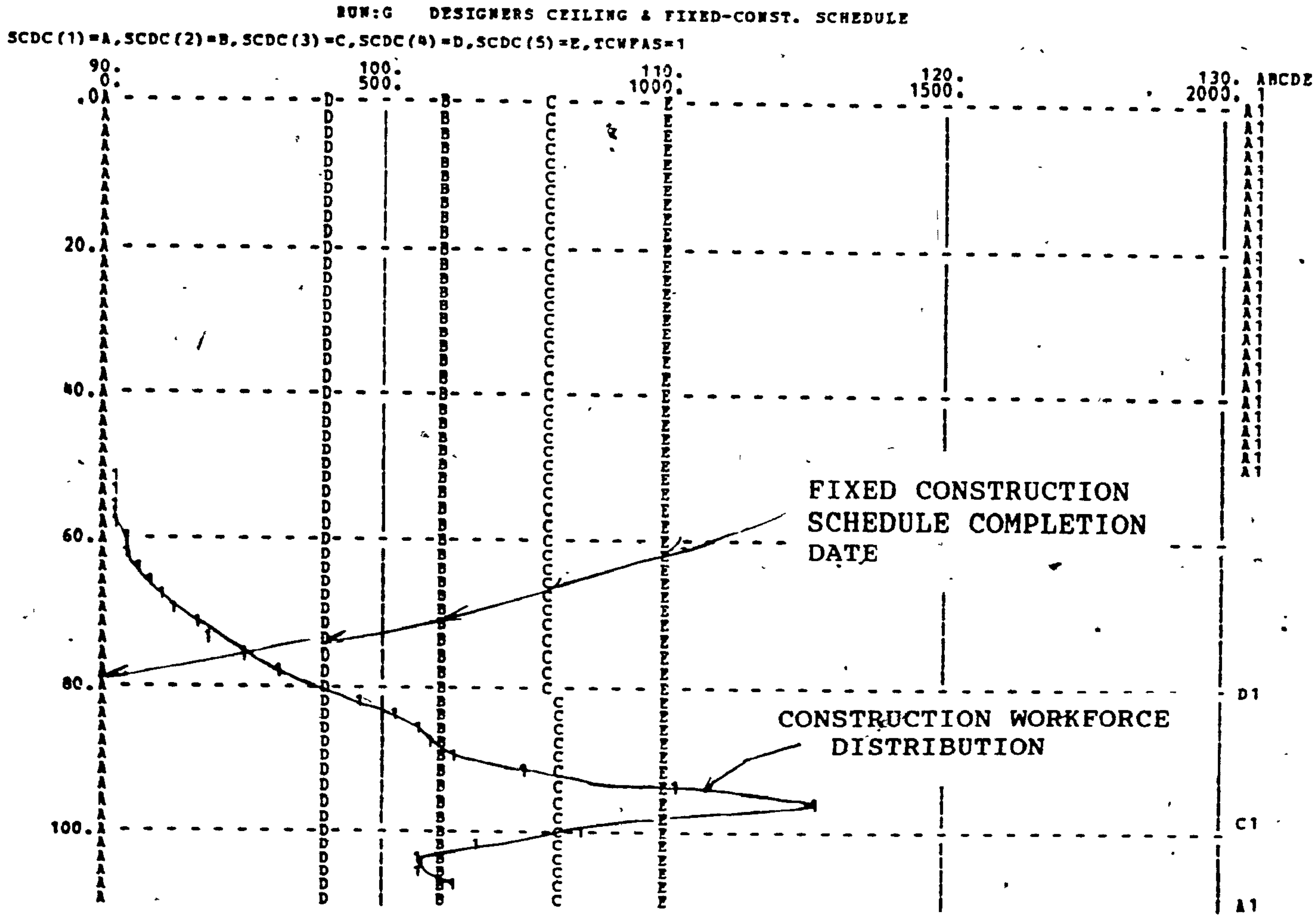


figure 81. Conventional project (Run G); fixed construction schedule and a ceiling on designer workforce

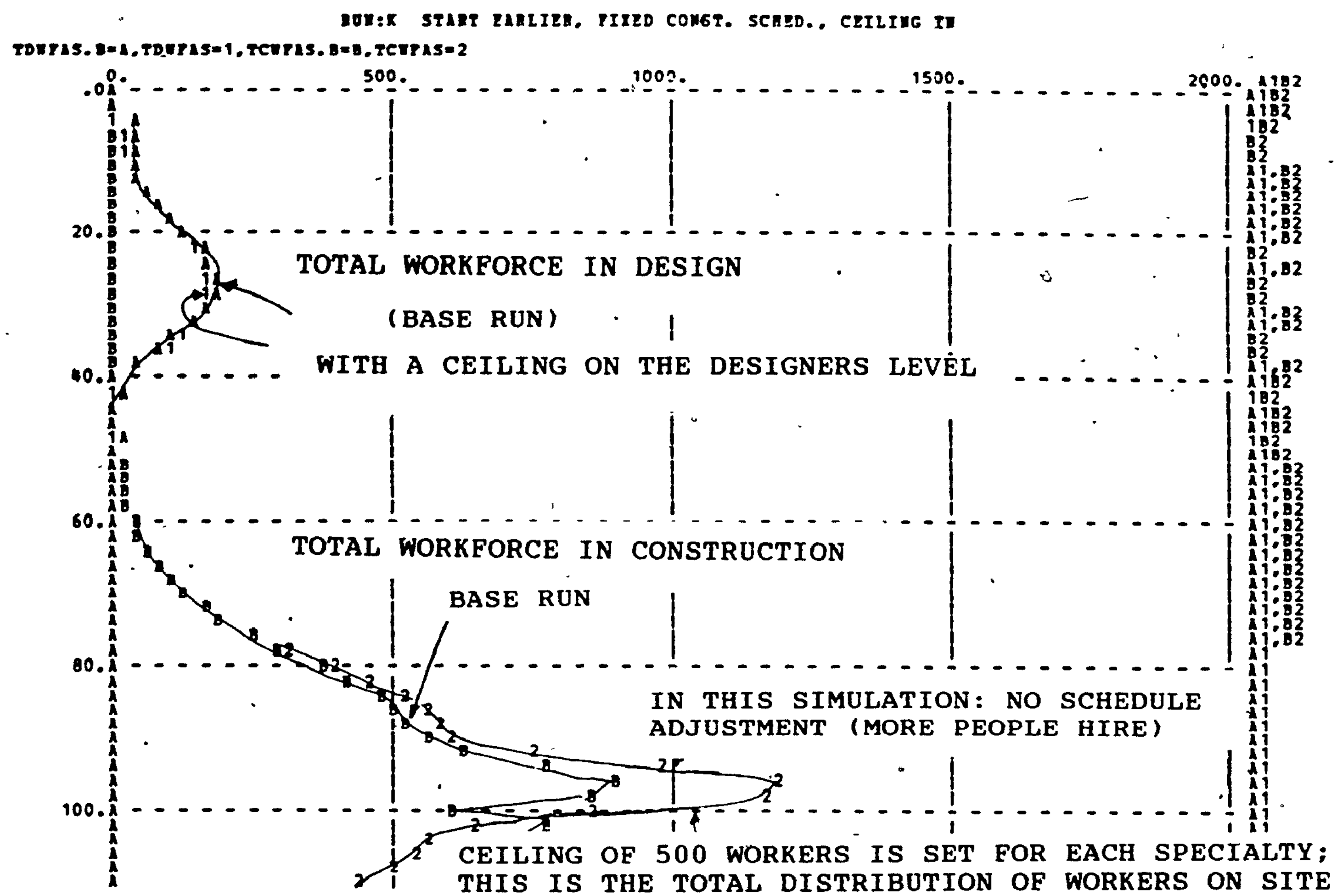


figure 82. Conventional project (Run K);
fixed schedules (const and design) and
a ceiling on workforce (design and const)

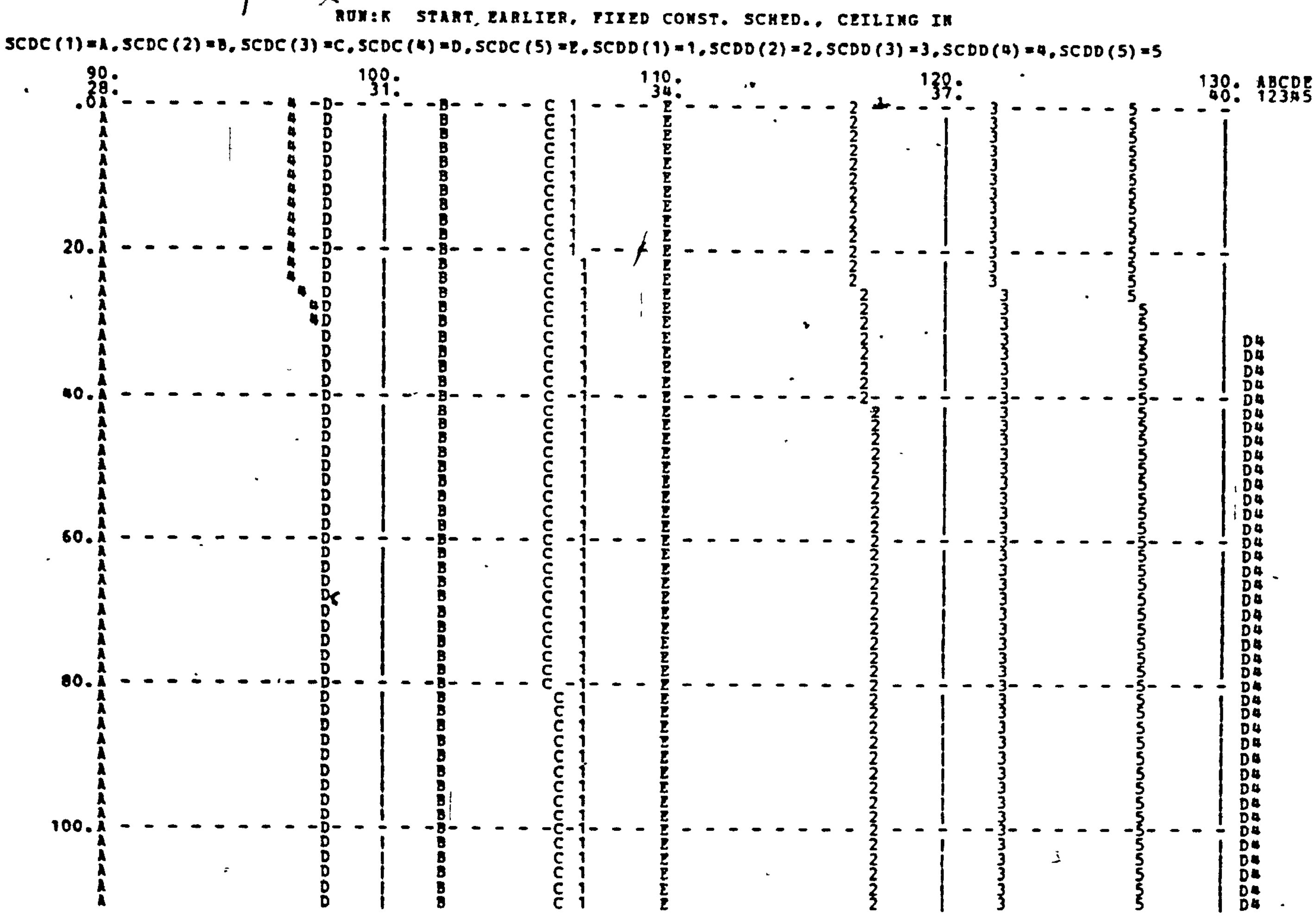


figure 83. Conventional project (Run K);
fixed schedules (const and design) and
a ceiling on workforce (design and const)

RUN:K START EARLIER, FIXED CONST. SCHED., CEILING IN

FPCONC(1)=A,FPCONC(2)=B,FPCONC(3)=C,FPCONC(4)=D,FPCONC(5)=E,TCWPAS=1

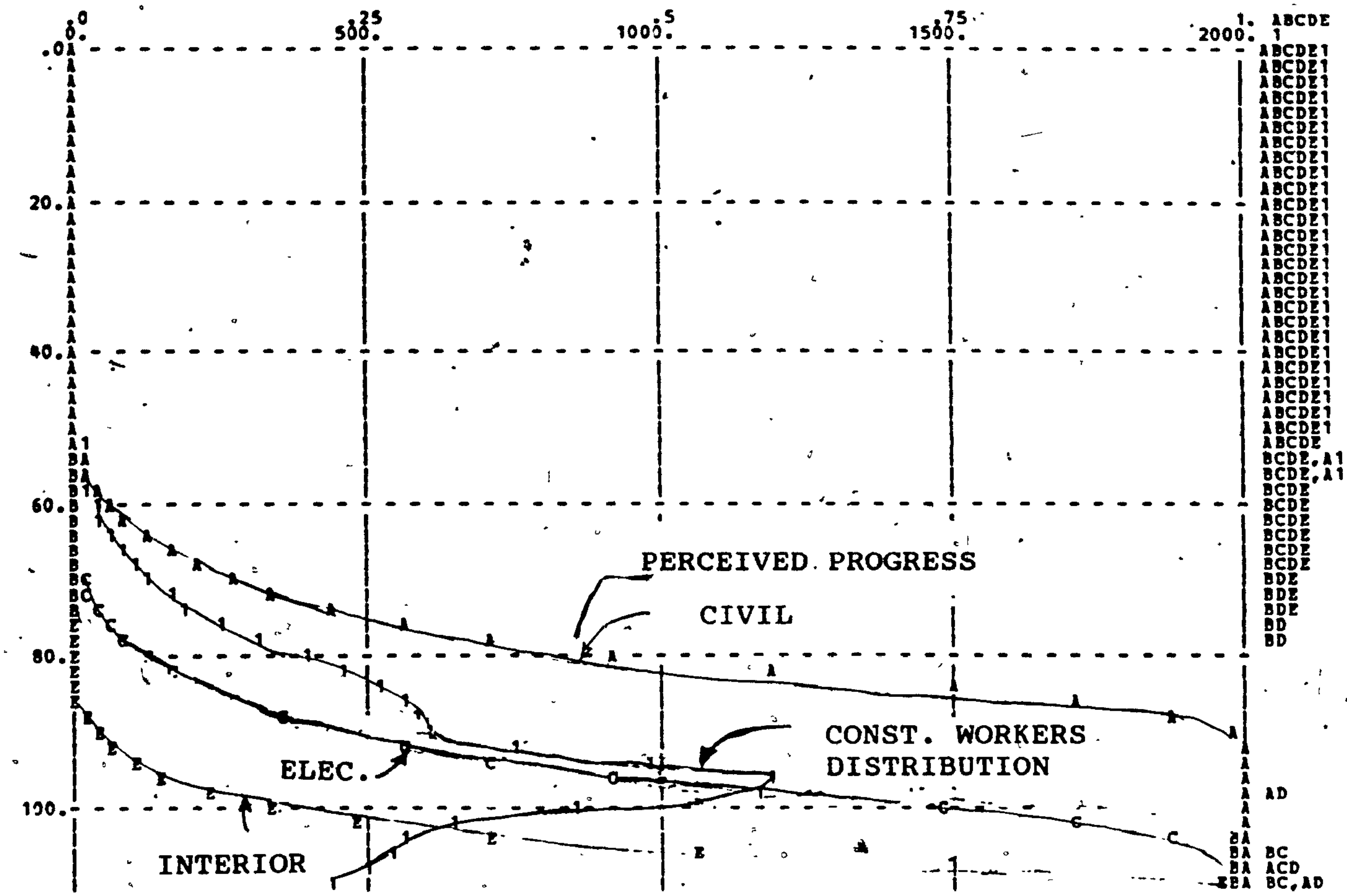


figure 84. Conventional project (Run K); fixed schedules (const and design) and a ceiling on workforce (design and const)

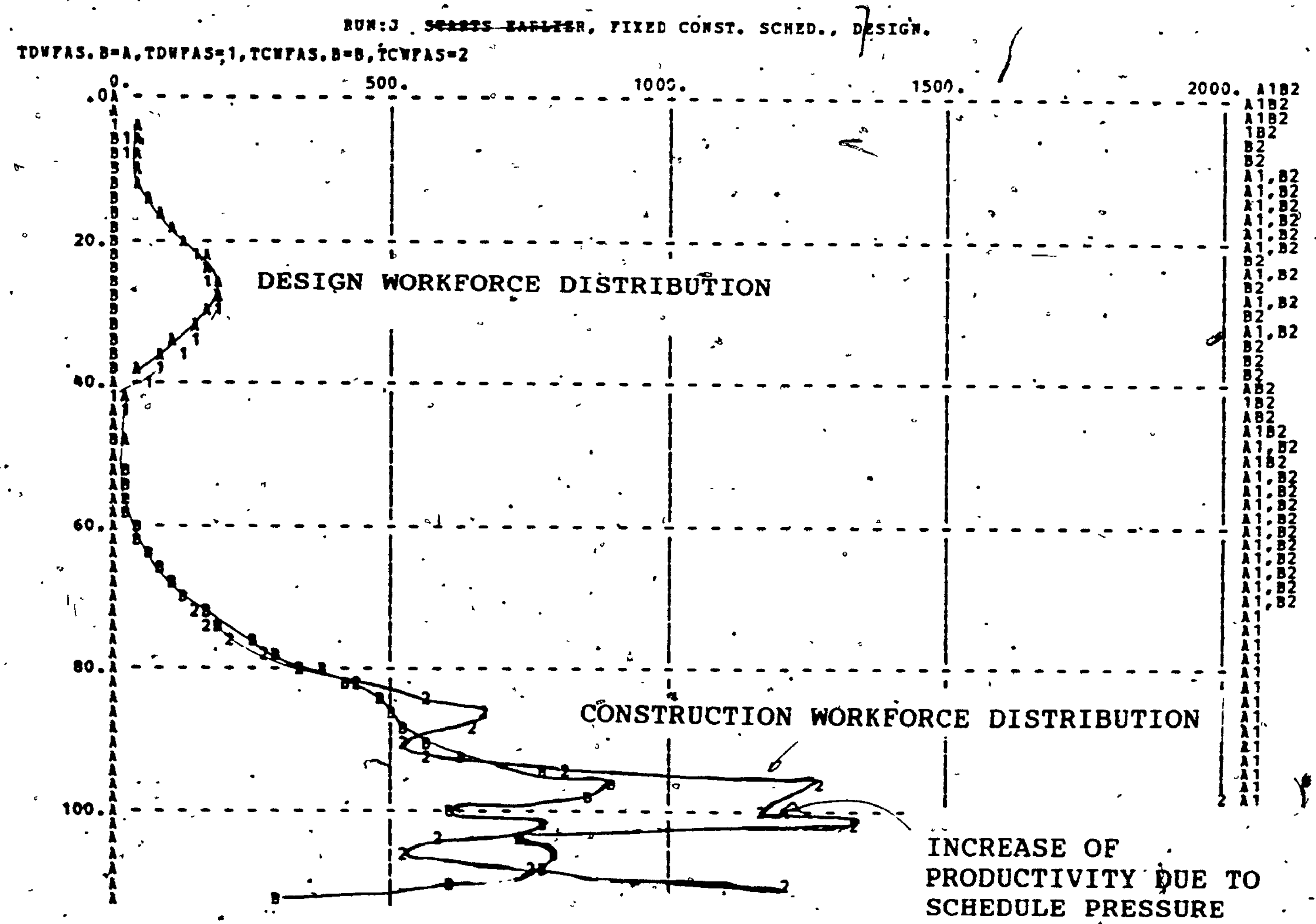


figure 85. Conventional project (Run J); fixed schedules (const and design), a ceiling on workforce in design and a willingness to recognize the schedule pressure

RUN J STARTS EARLIER, FIXED CONST. SCHED., DESIGN.

SCPEPC.B(1)=A,SCPEPC.B(2)=B,SCPEPC.B(3)=C,SCPEPC.B(4)=D,SCPEPC.B(5)=E,SCPEPC(1)=1,SCPEPC(2)=2,SCPEPC(3)=3,
SCPEPC(4)=4,SCPEPC(5)=5

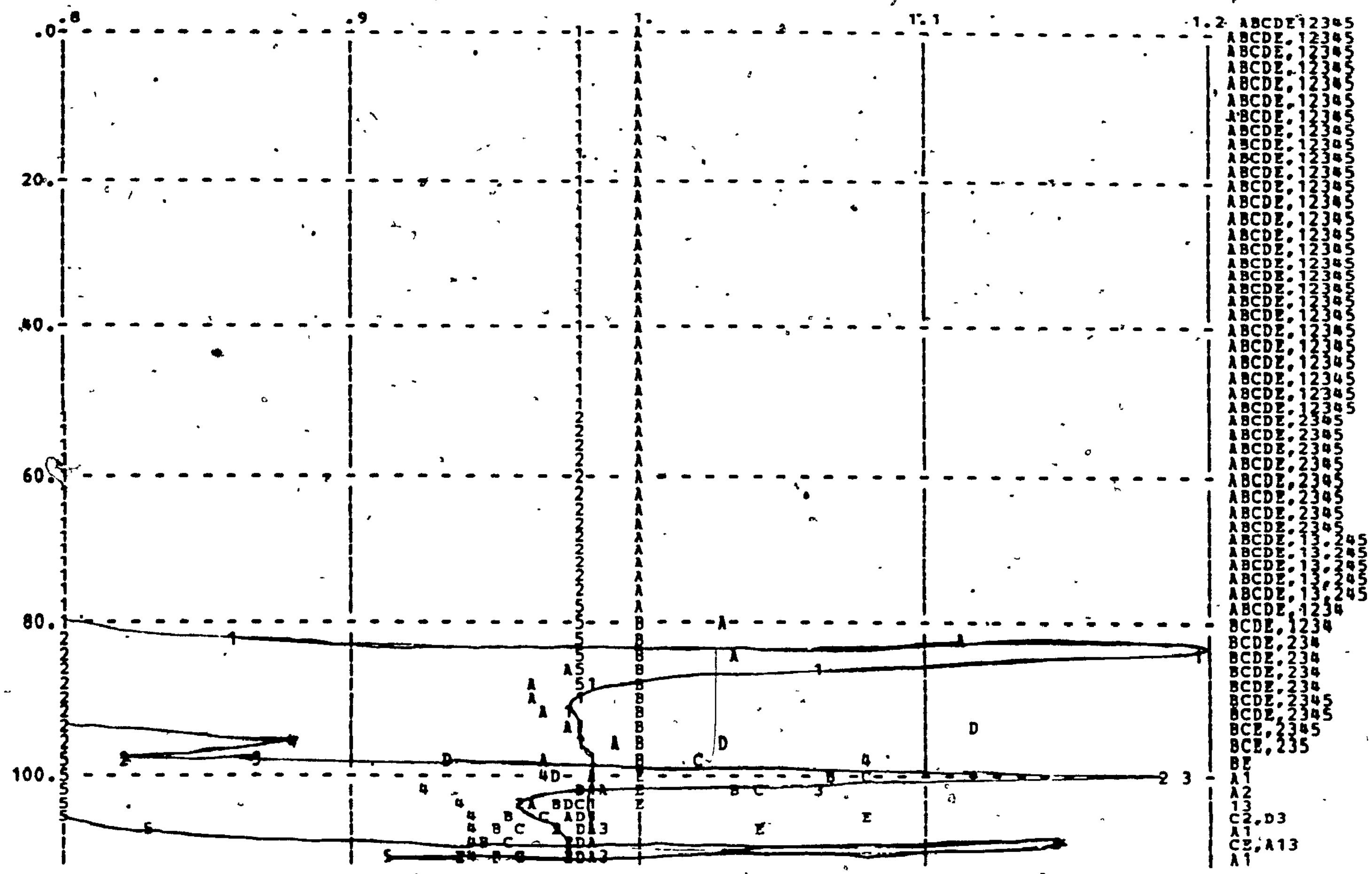


figure 86. Conventional project (Run J); fixed schedules (const and design), a ceiling on workforce in design and a willingness to recognize the schedule pressure

RUN:J ~~STARTS EARLIER~~, FIXED CONST. SCHED., DESIGN.

SCPEQC.B(1)=A,SCPEQC.B(2)=B,SCPEQC.B(3)=C,SCPEQC.B(4)=D,SCPEQC.B(5)=E,SCPEQC(1)=1,SCPEQC(2)=2,SCPEQC(3)=3,
SCPEQC(4)=4,SCPEQC(5)=5

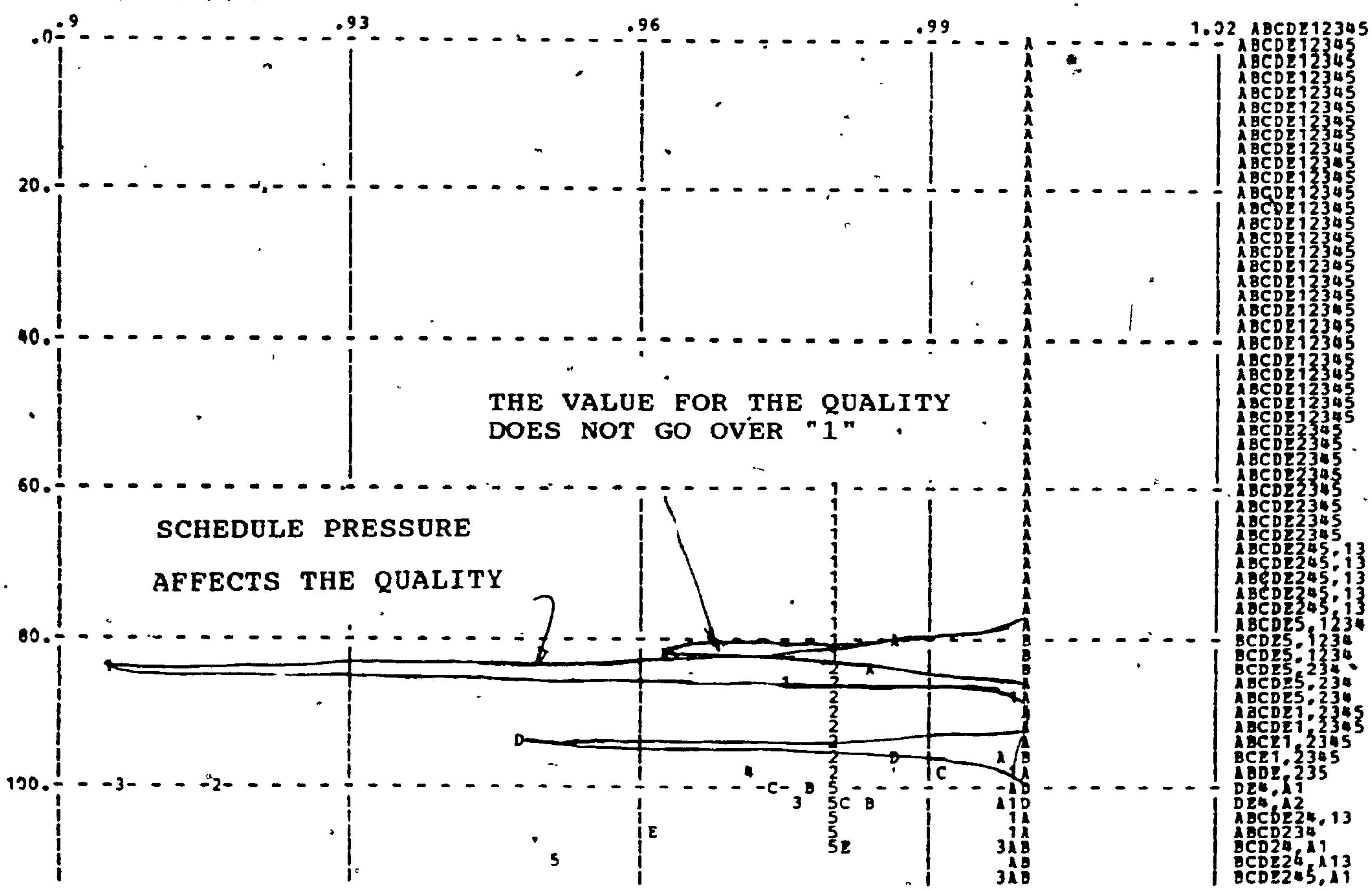


figure 87. **Conventional project (Run J); fixed schedules (const and design), a ceiling on workforce in design and a willingness to recognize the schedule pressure**

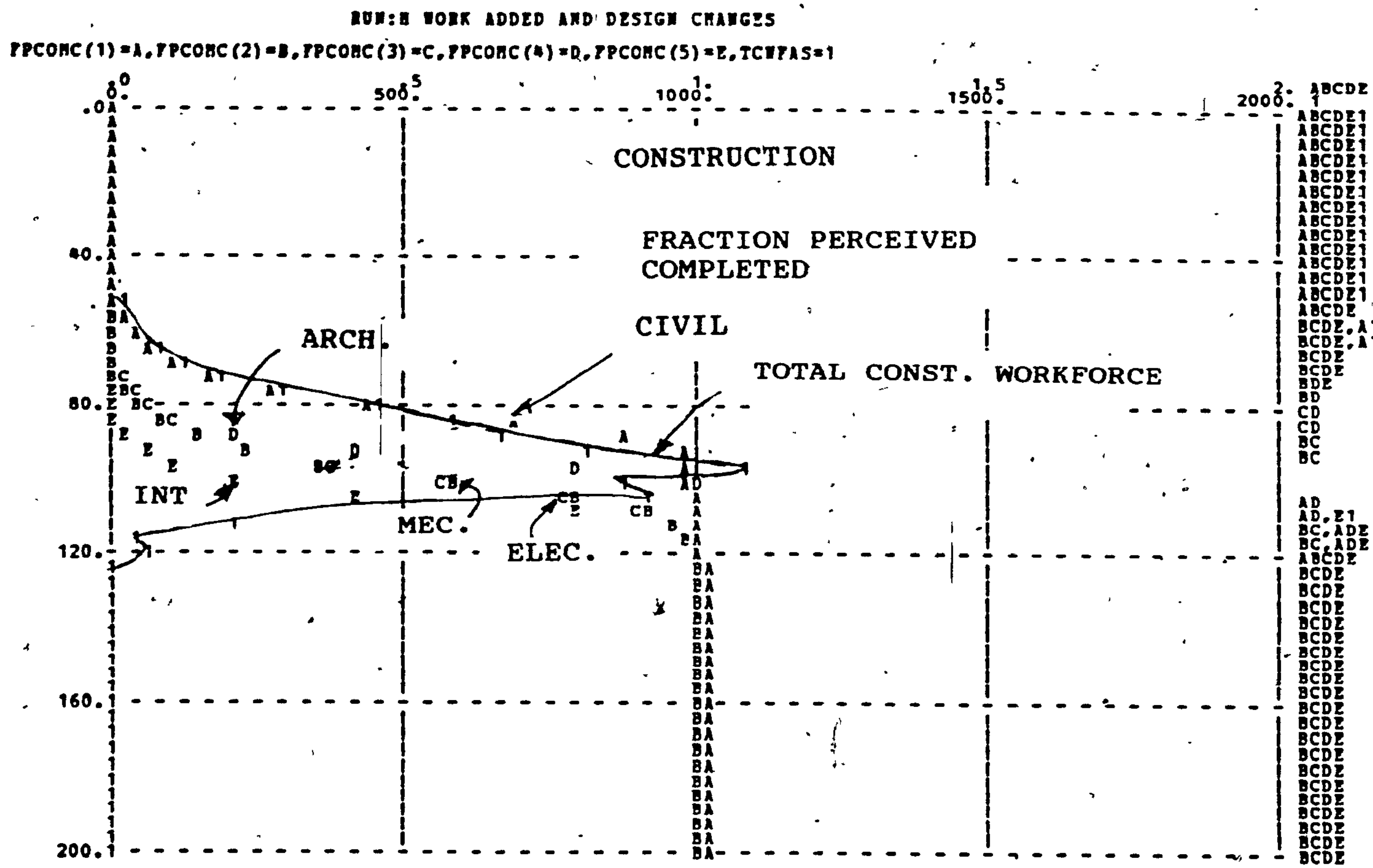


figure 88. Conventional project (Run H); work added and design change

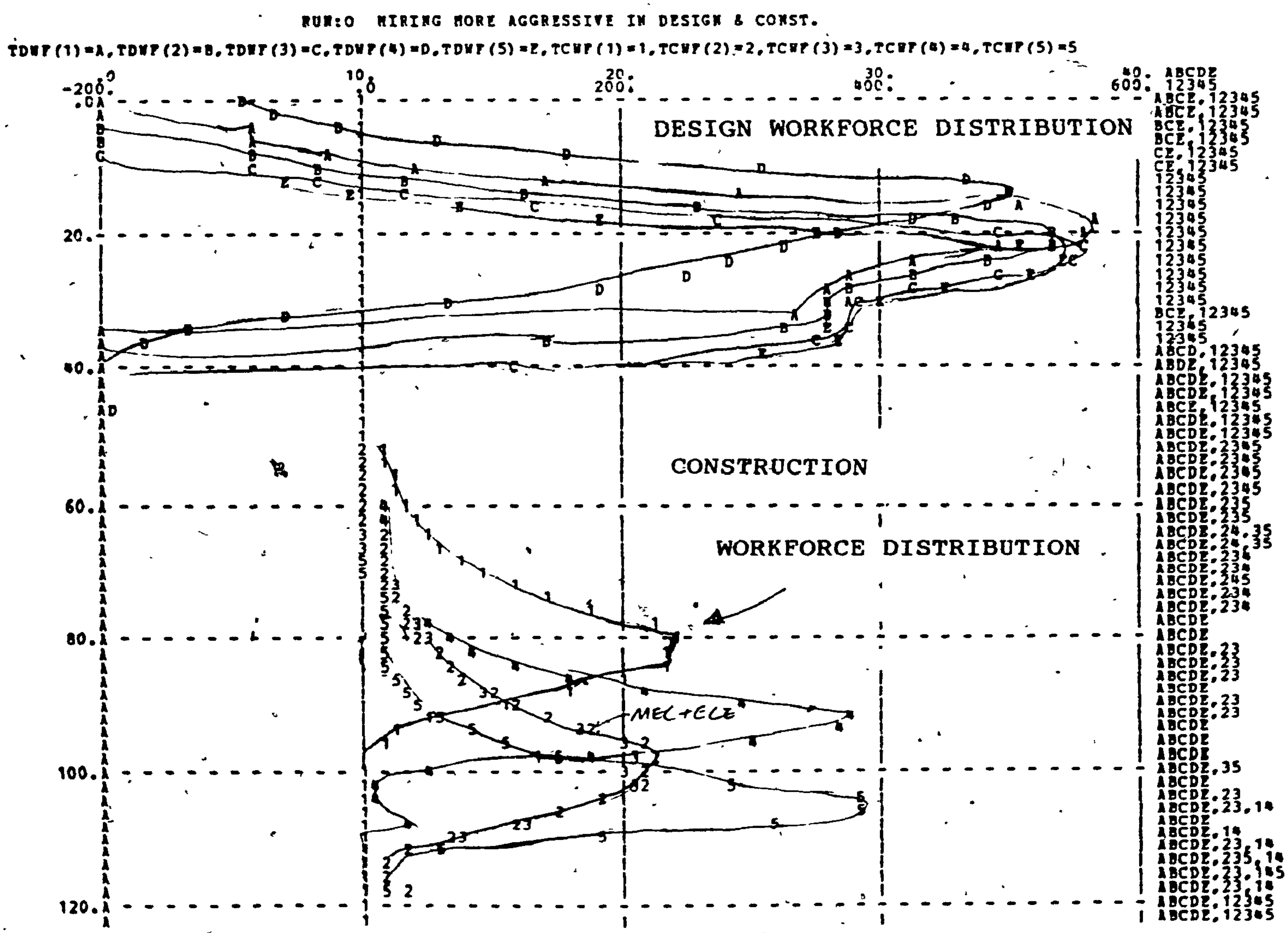


figure 89. Conventional project (Run H); more aggressive to hire workers

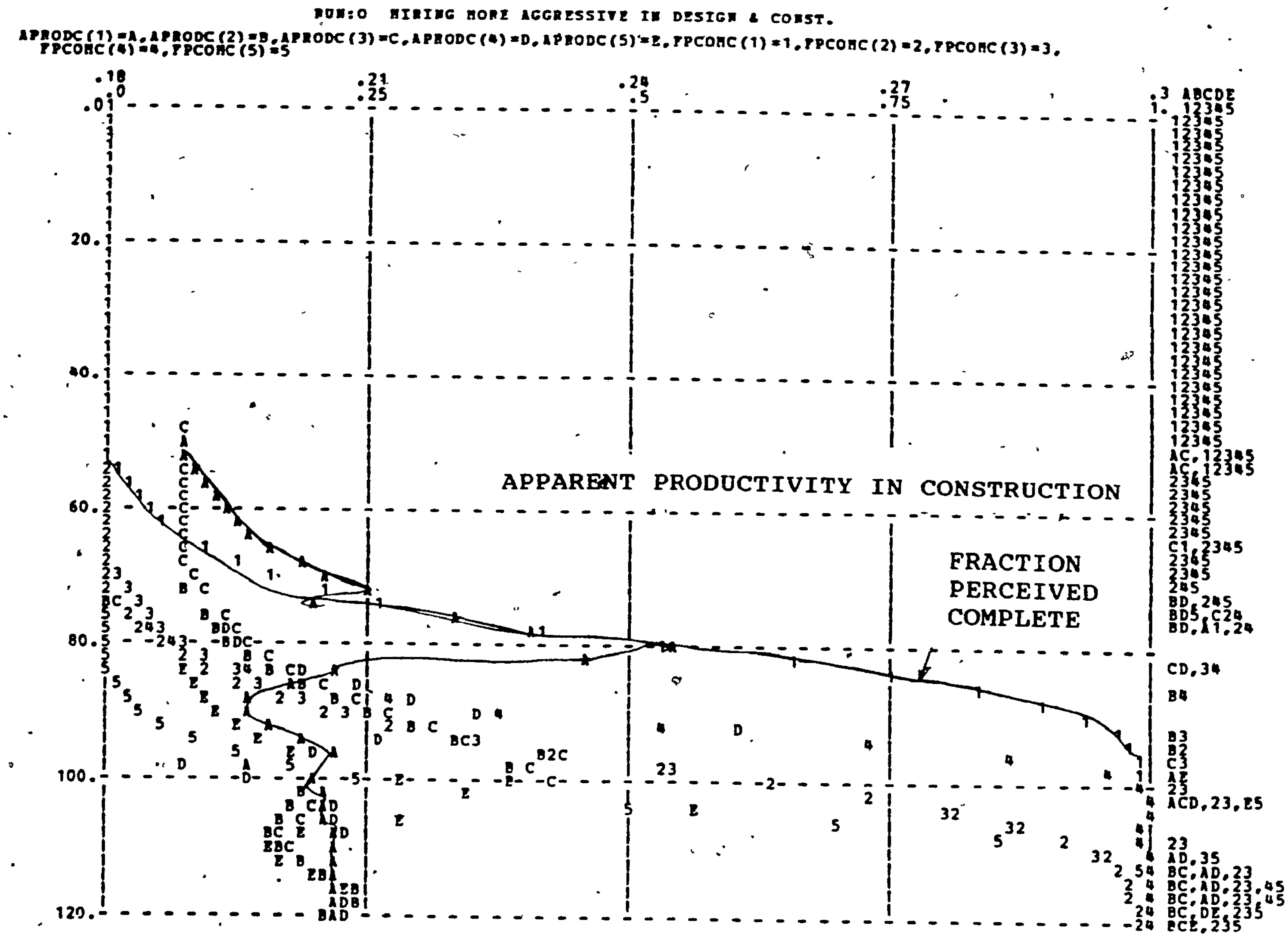


figure 90: Conventional project (Run H); more aggressive to hire workers

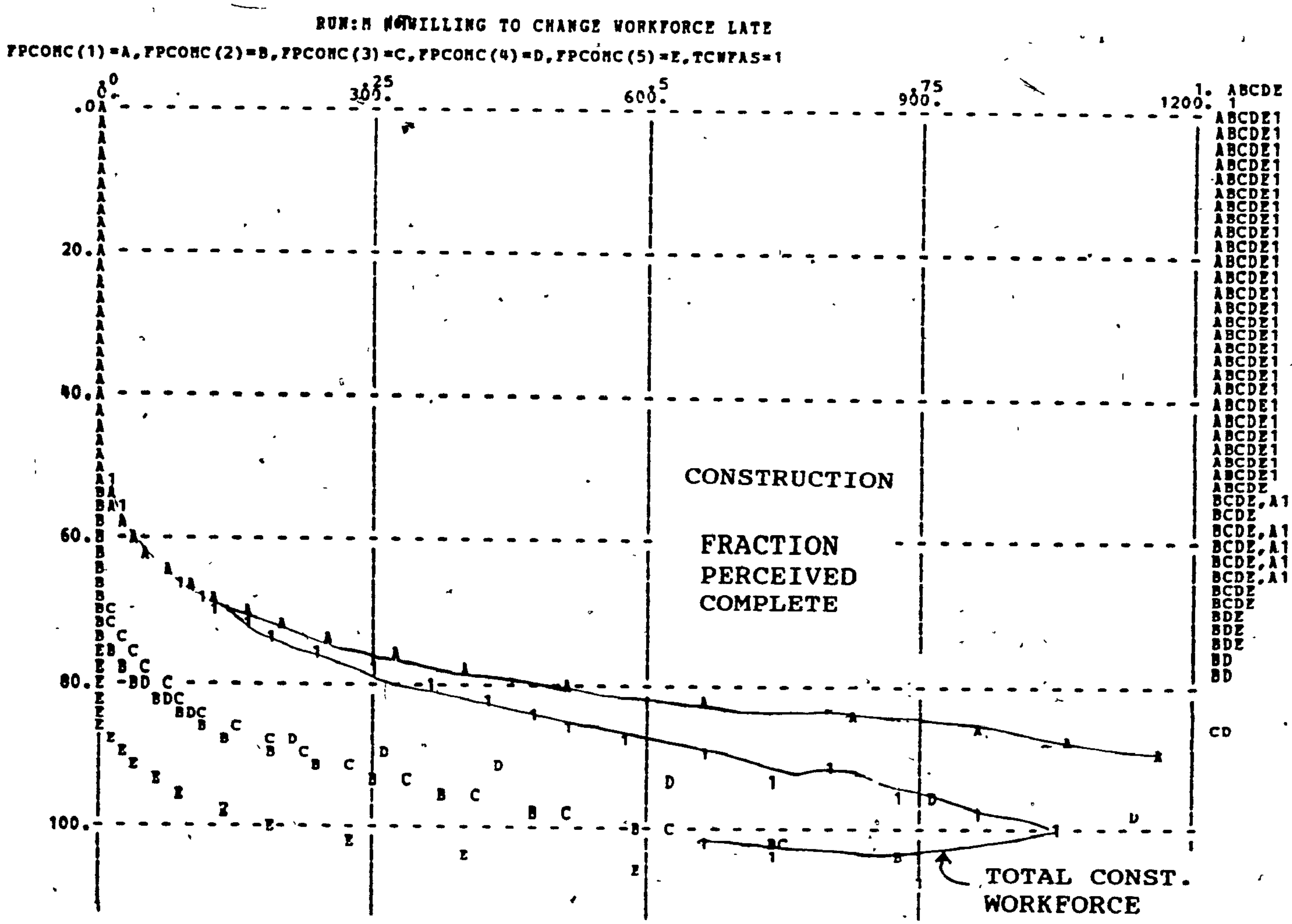


figure 91. Conventional project (Run M); not willing to change const workers near the end of the project

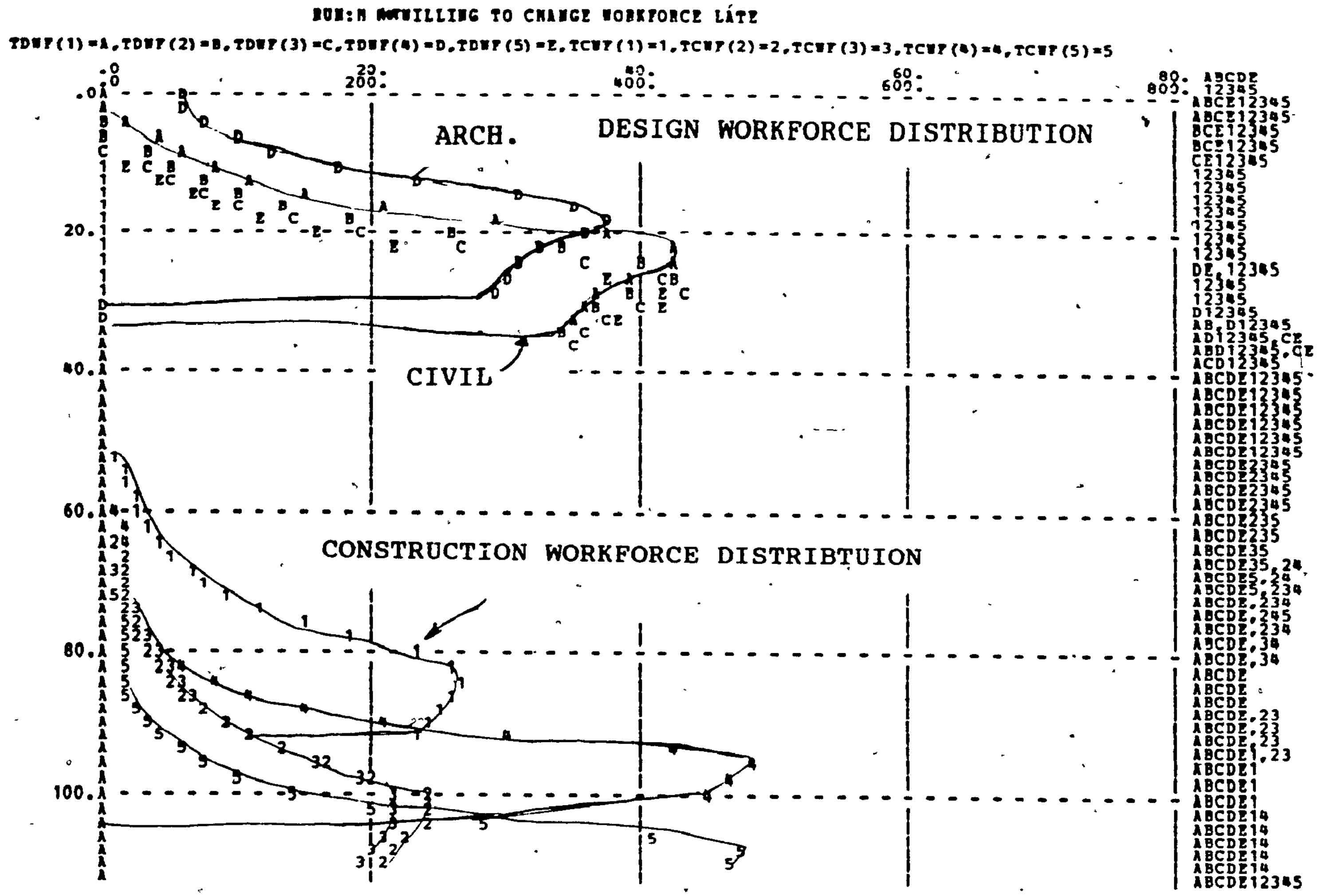


figure 92. Conventional project (Run M); not willing to change const workers near the end of the project

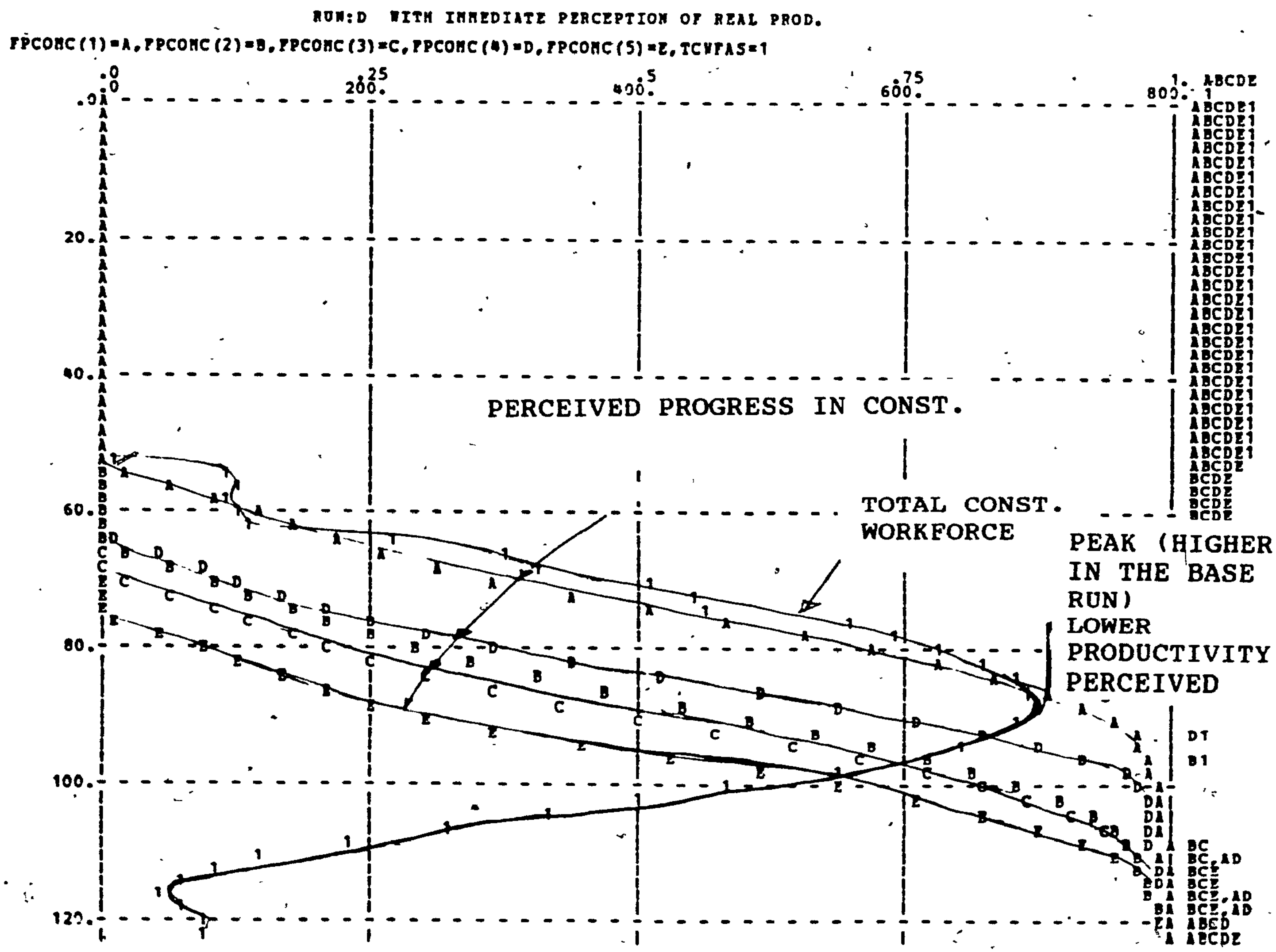


figure 93. Conventional project (Run D); willing to recognize the real productivity (design and const)

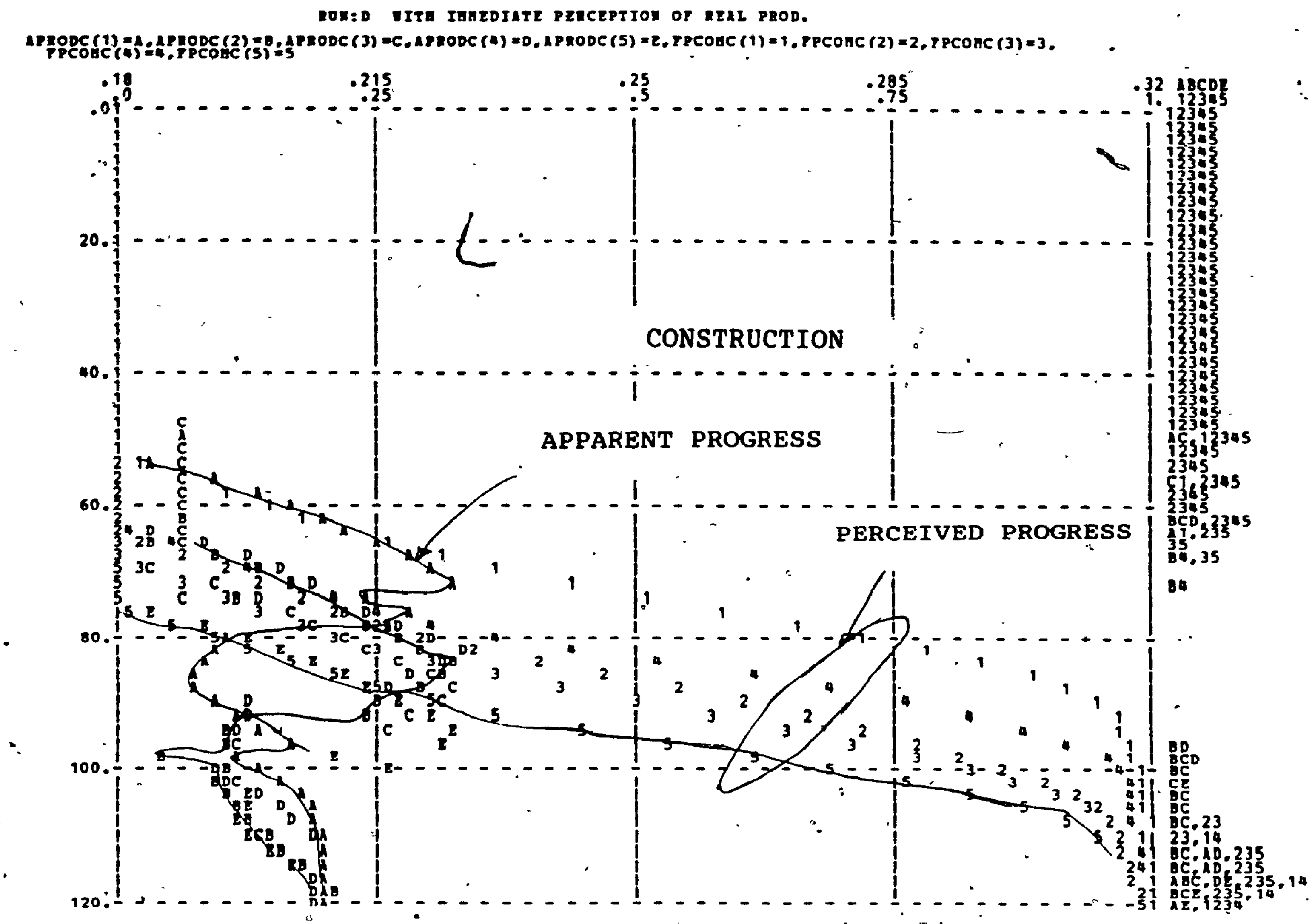


figure 94. Conventional project (Run D); willing to recognize the real productivity (design and const)

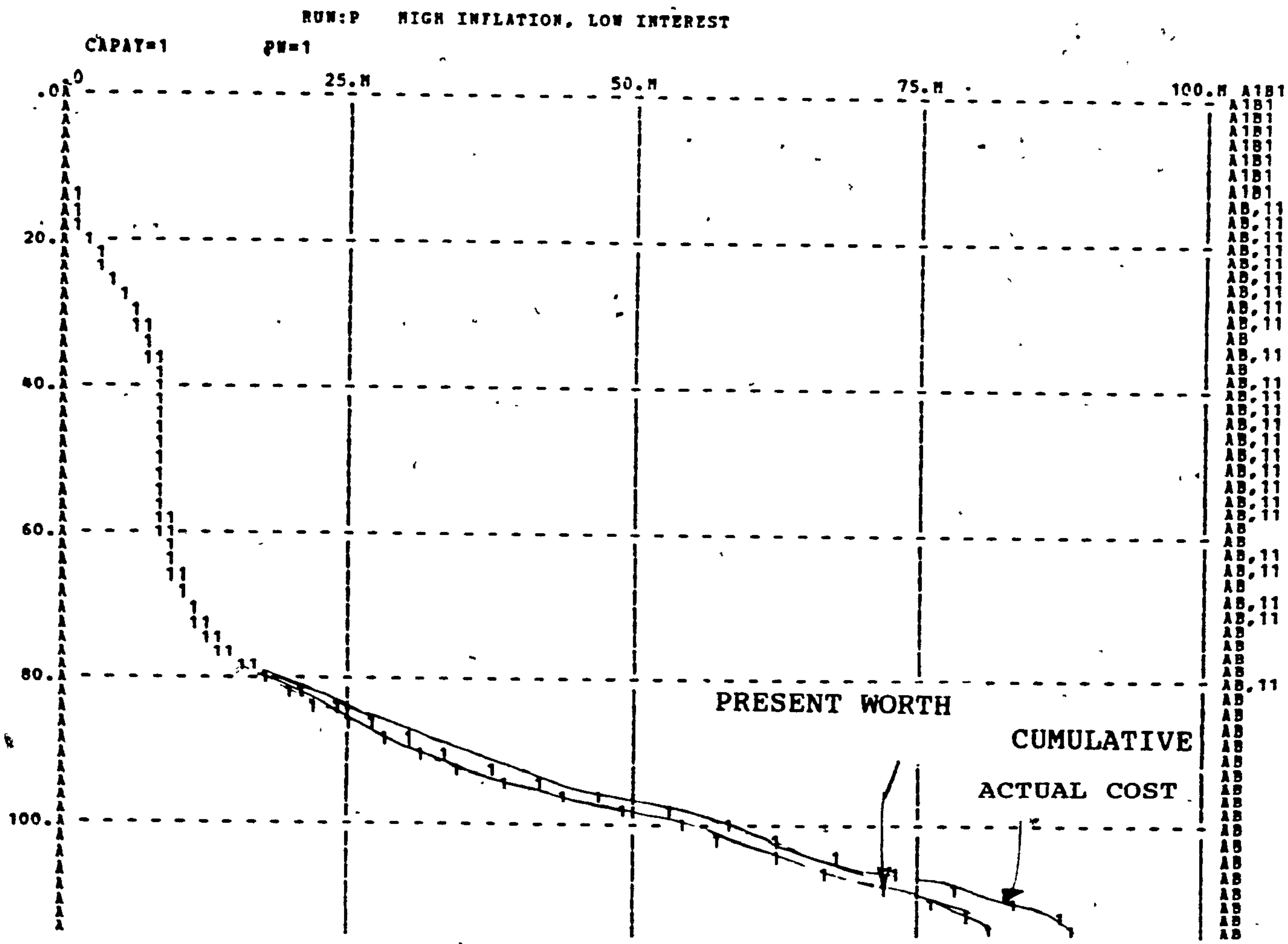


figure 95. Conventional project (Run P);
inflation rate: 15%
interest rate: 5%

RUN:P HIGH INFLATION, LOW INTEREST

FPCONC(1)=A,FPCONC(2)=B,FPCONC(3)=C,FPCONC(4)=D,FPCONC(5)=E,TCWFAS=1

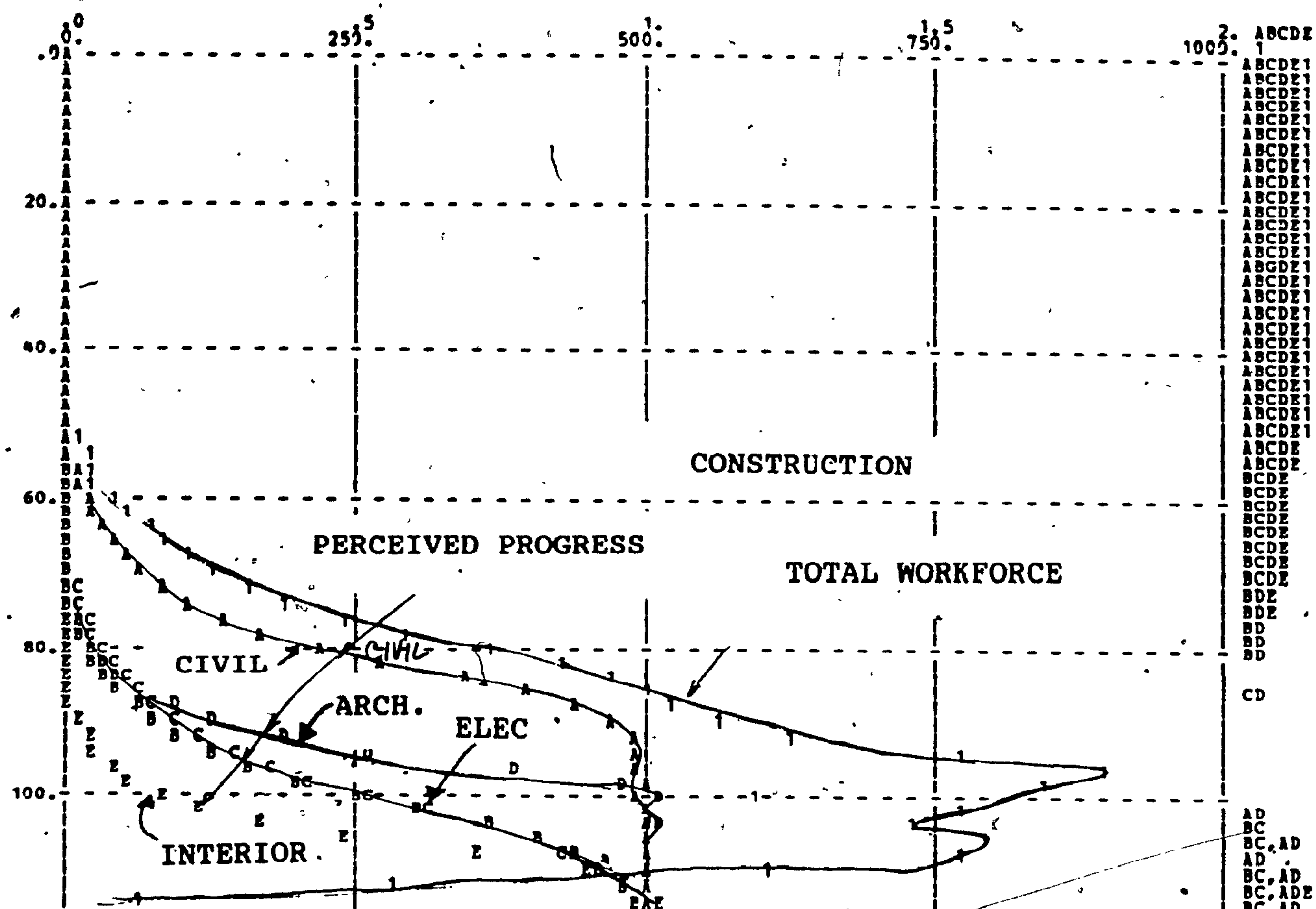


figure 96. Conventional project (Run P);
inflation rate: 15%
interest rate: 5%

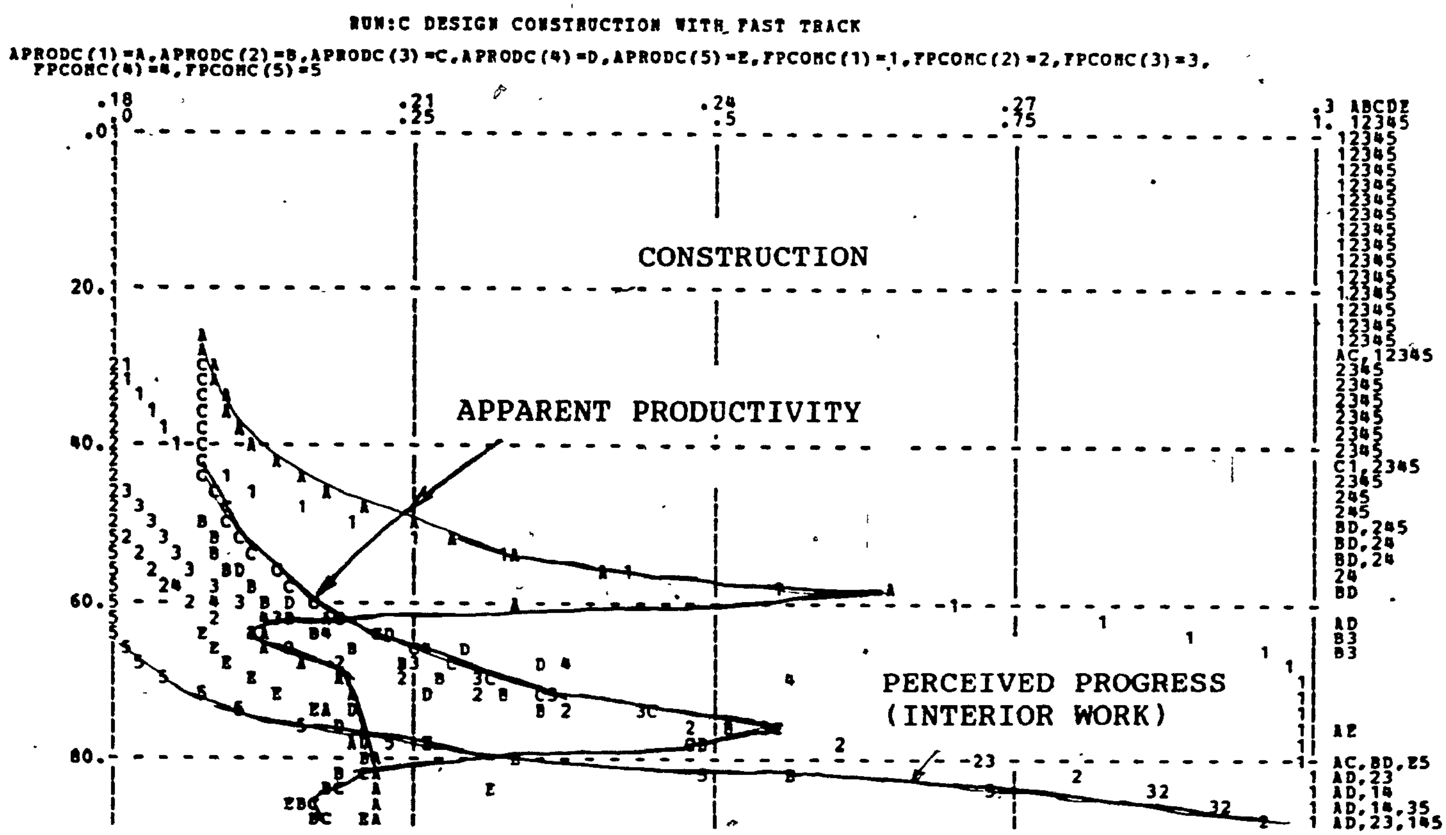


figure 97. Fast-track project; run C

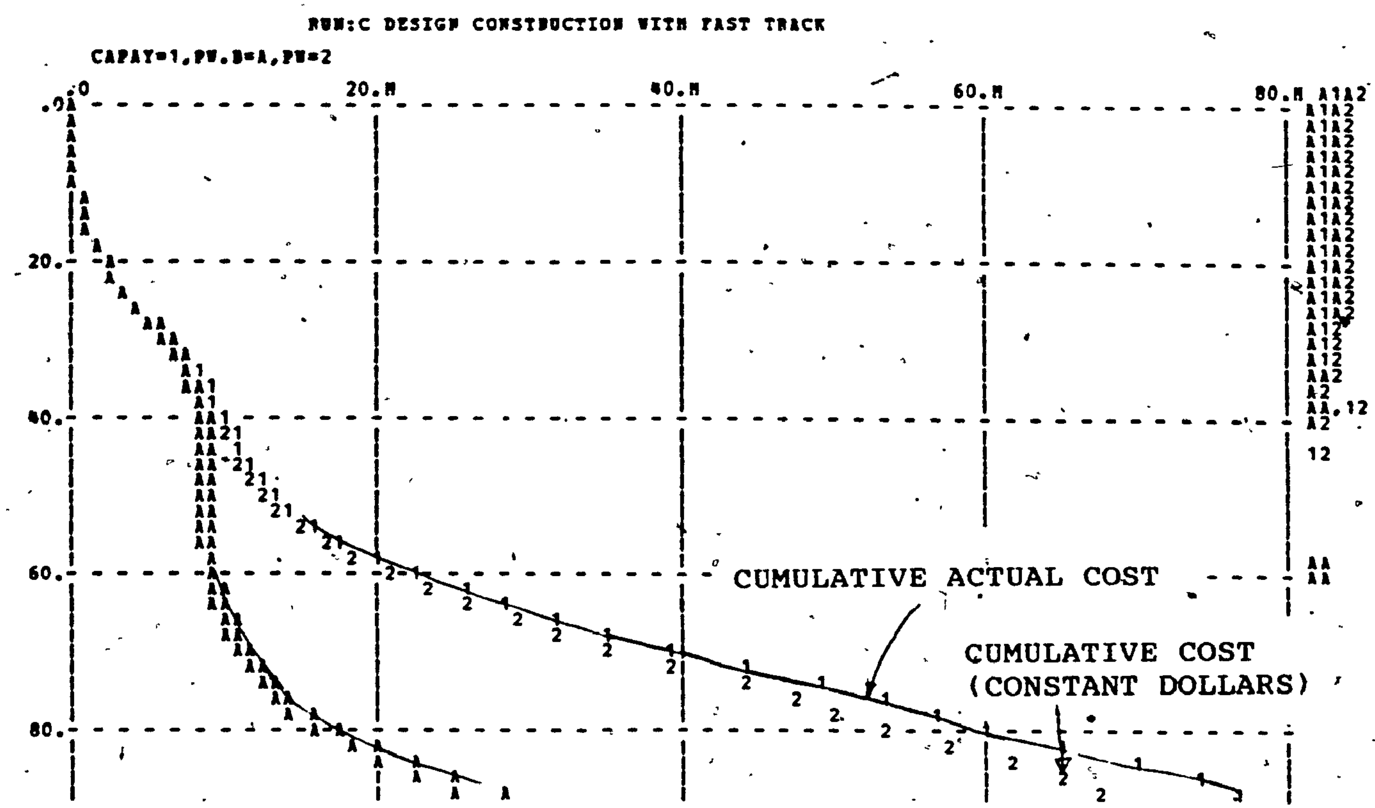


figure 98. Fast-track project; run C

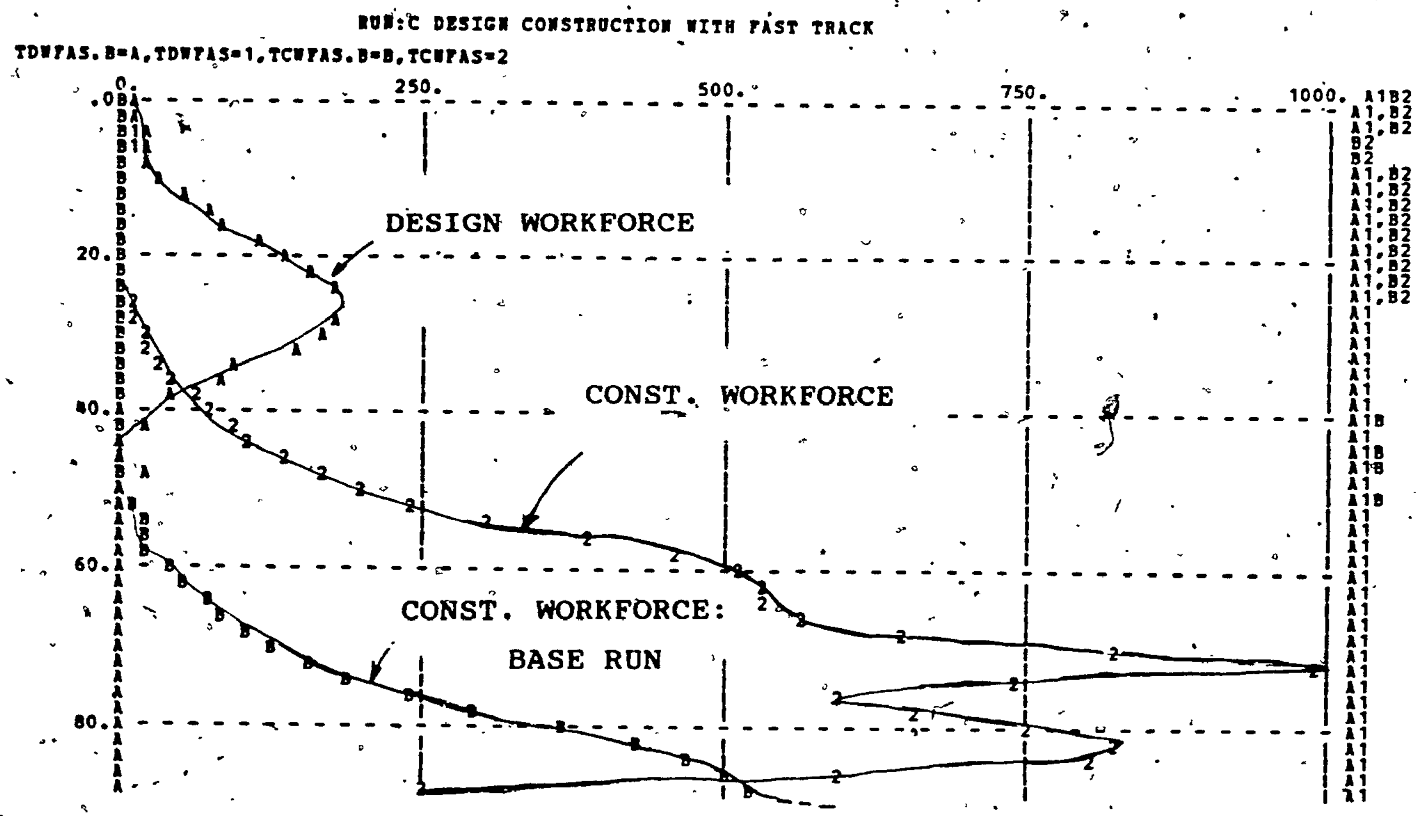


figure 99. Fast-track project; run C

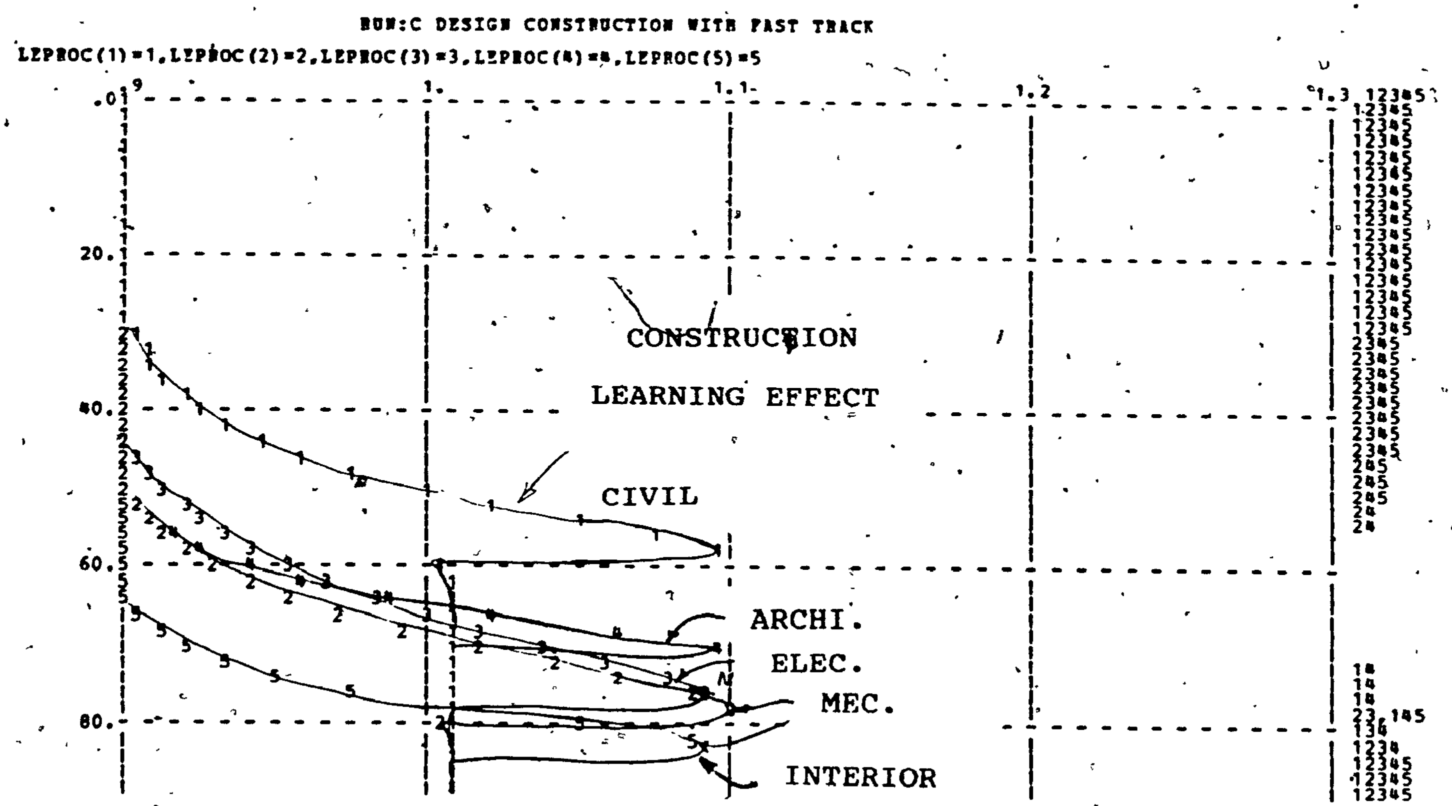


figure 100. Fast-track project; run C

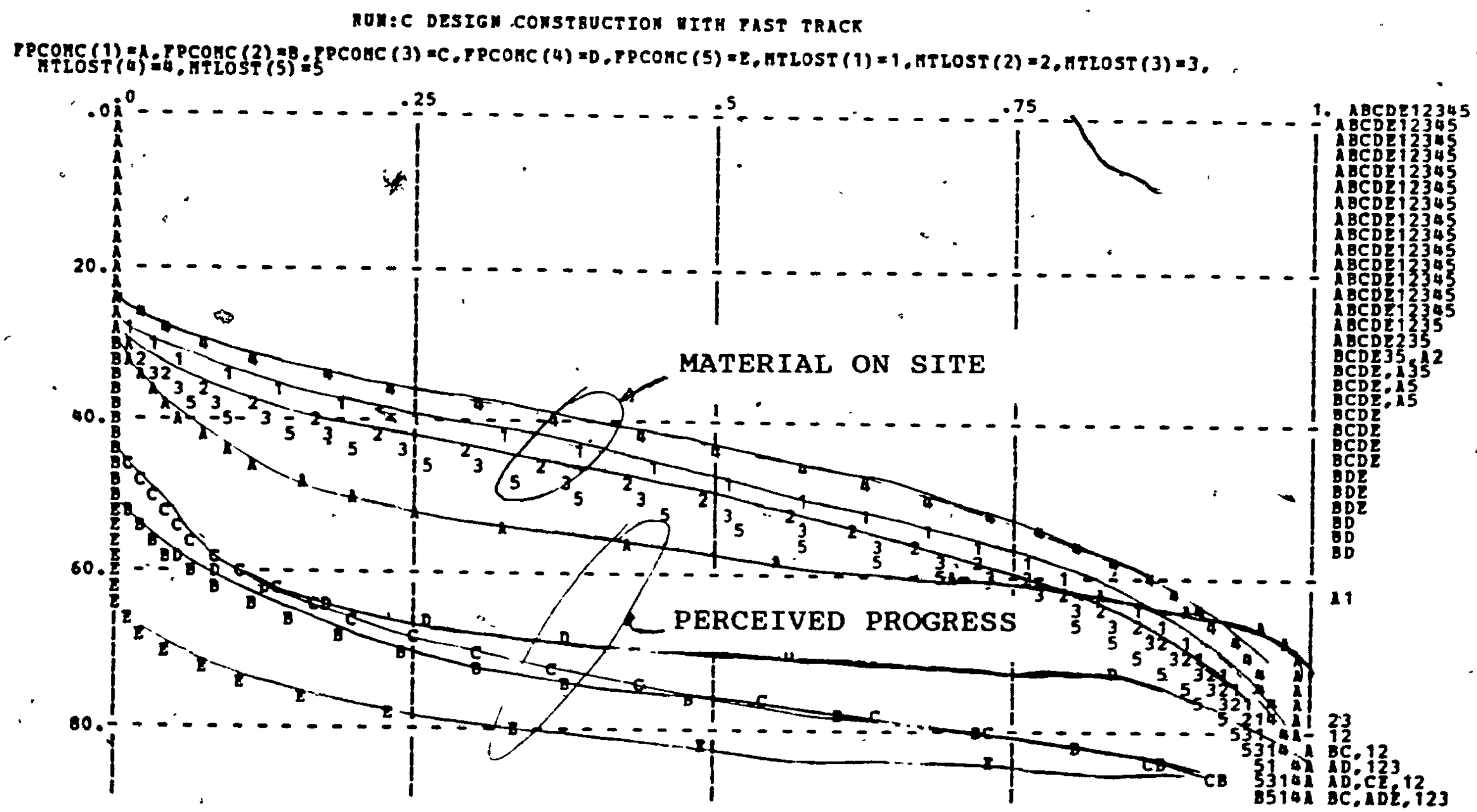


figure 101. Fast-track project; run C

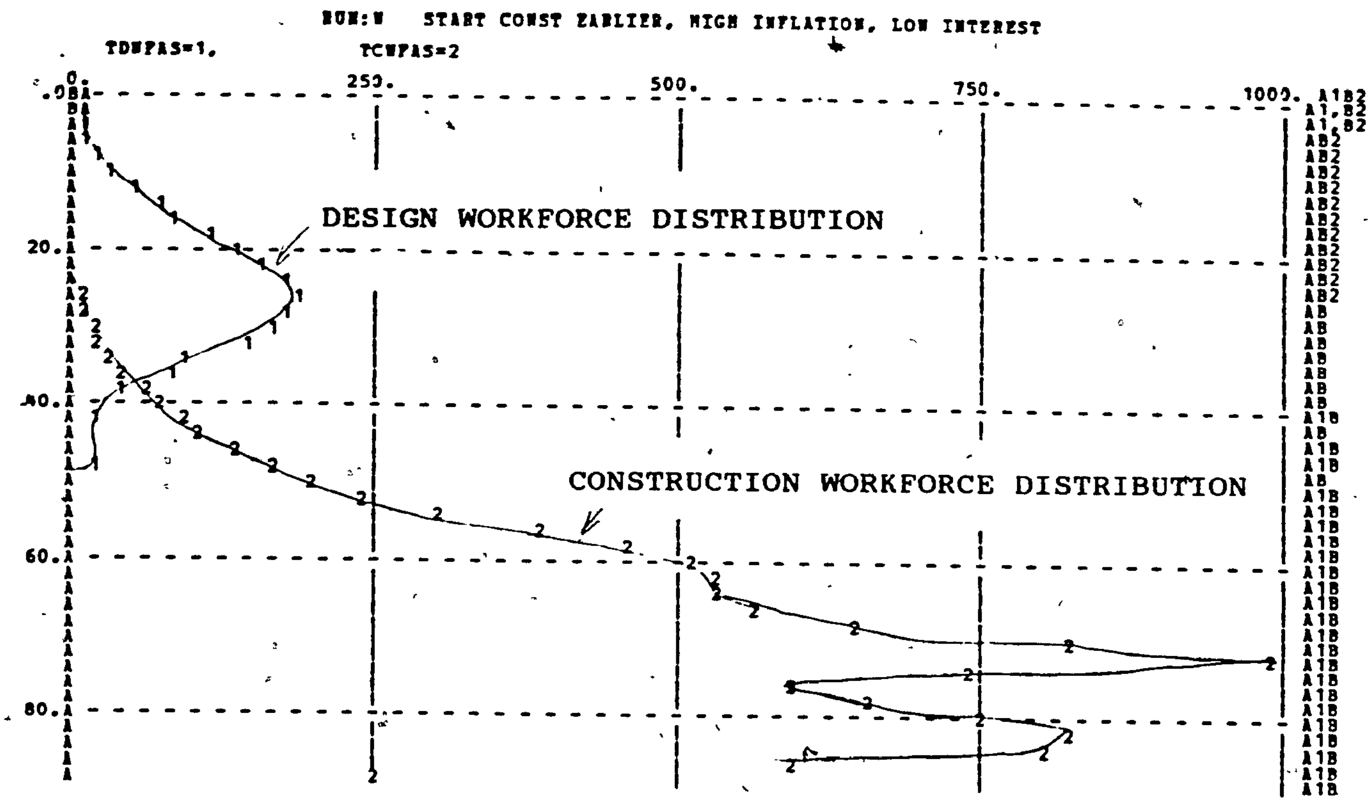


figure 102. Fast-track project; run w
inflation rate:15%,
interest rate:5%

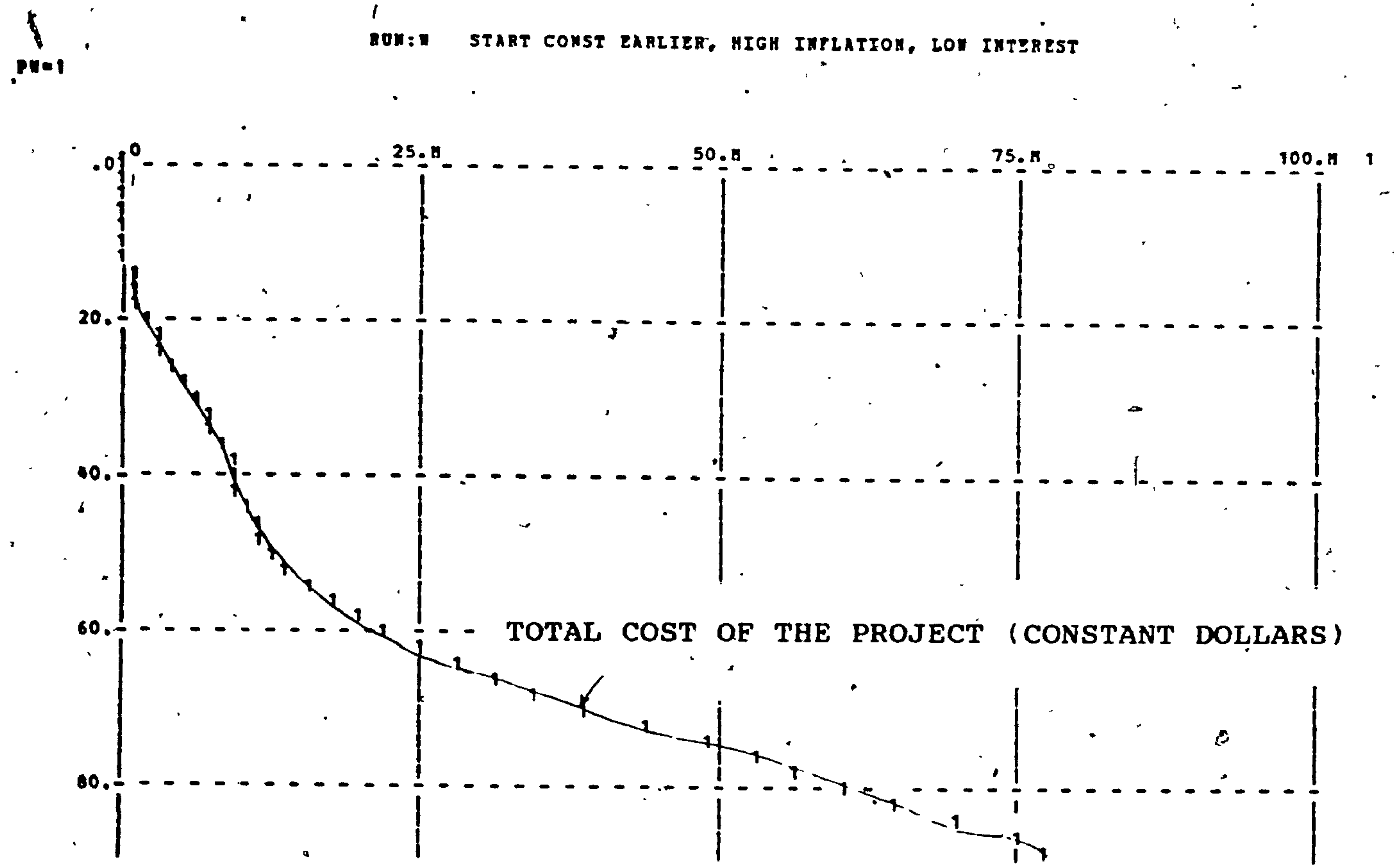


figure 103. Fast-track project; run W
inflation rate:15%,
interest rate:5%

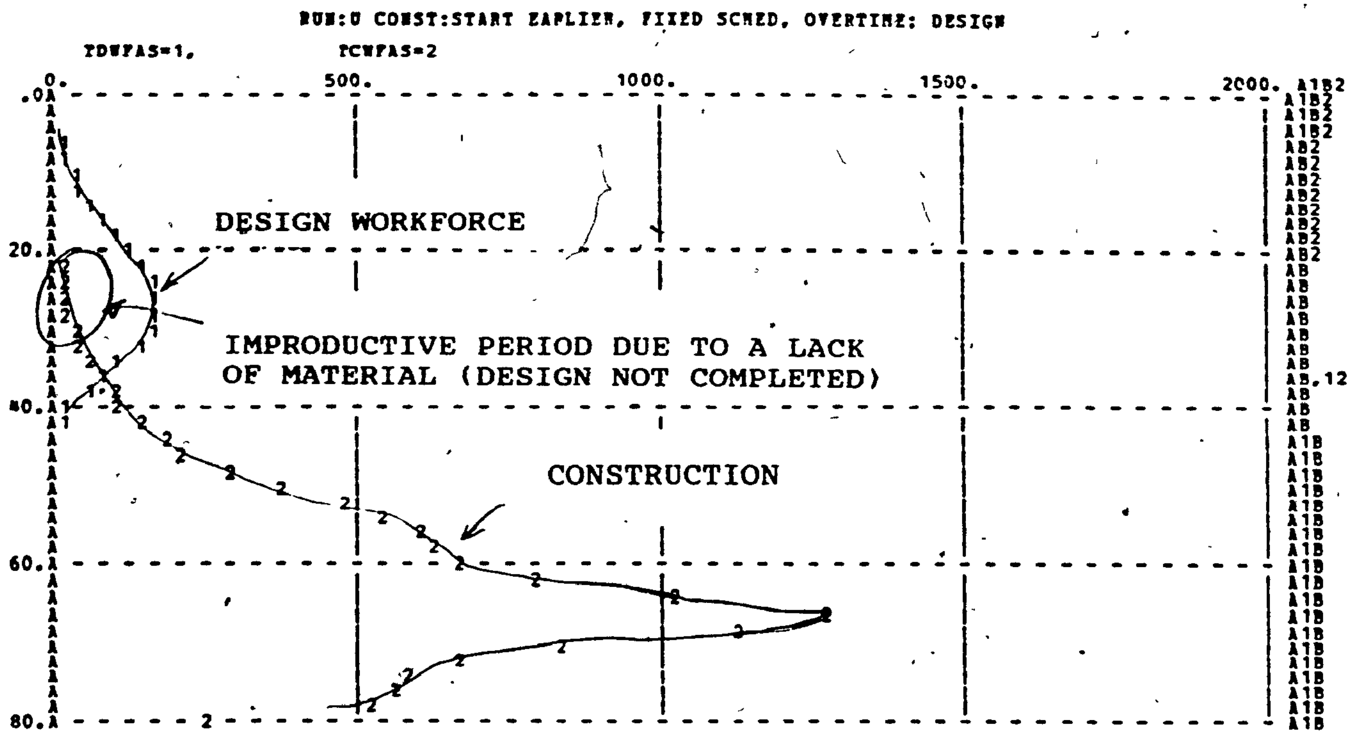


figure 104. Fast-track project; run U, fixed construction schedule, willingness to work on overtime due to acceleration or schedule pressure

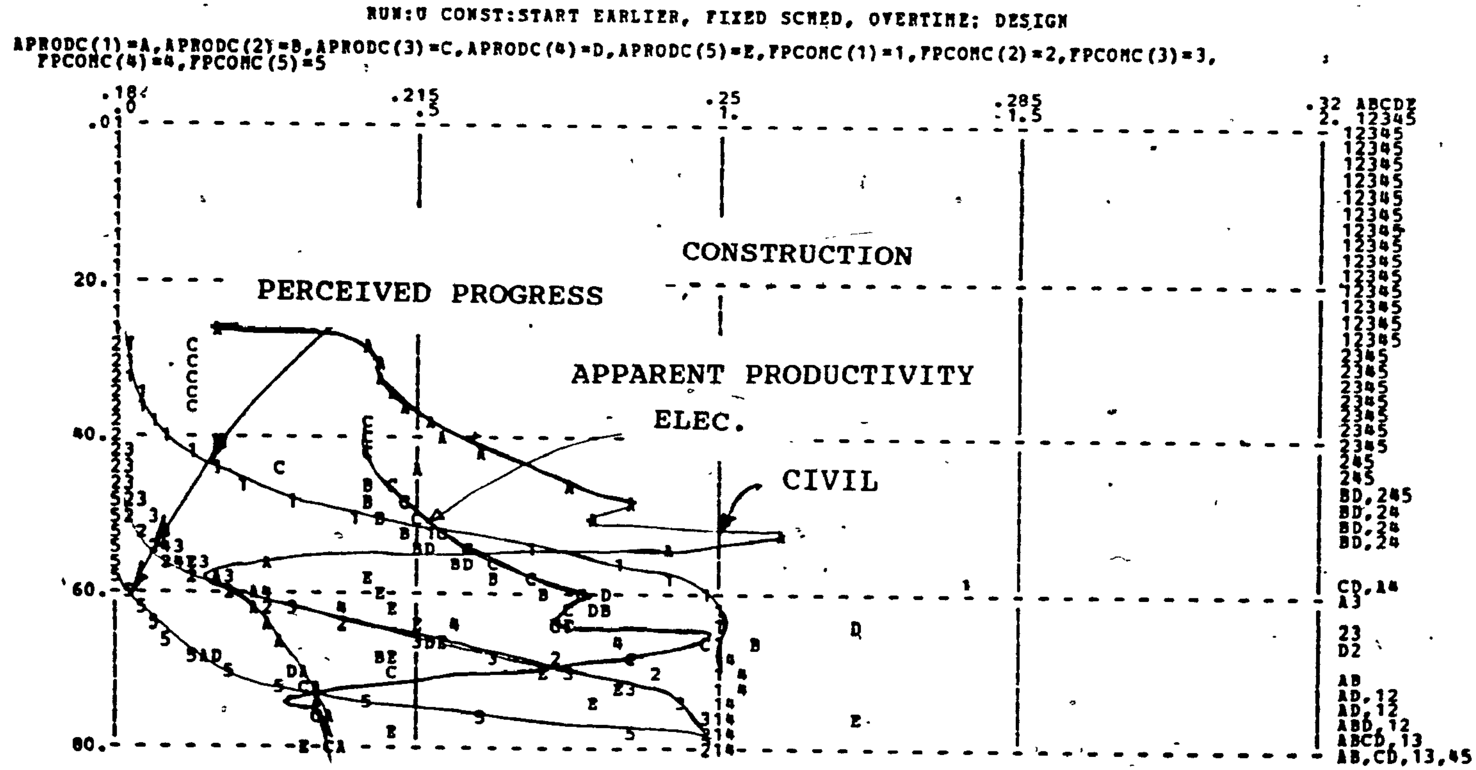


figure 105. Fast-track project; run U,
fixed construction schedule,
willingness to work on overtime
due to acceleration or schedule pressure

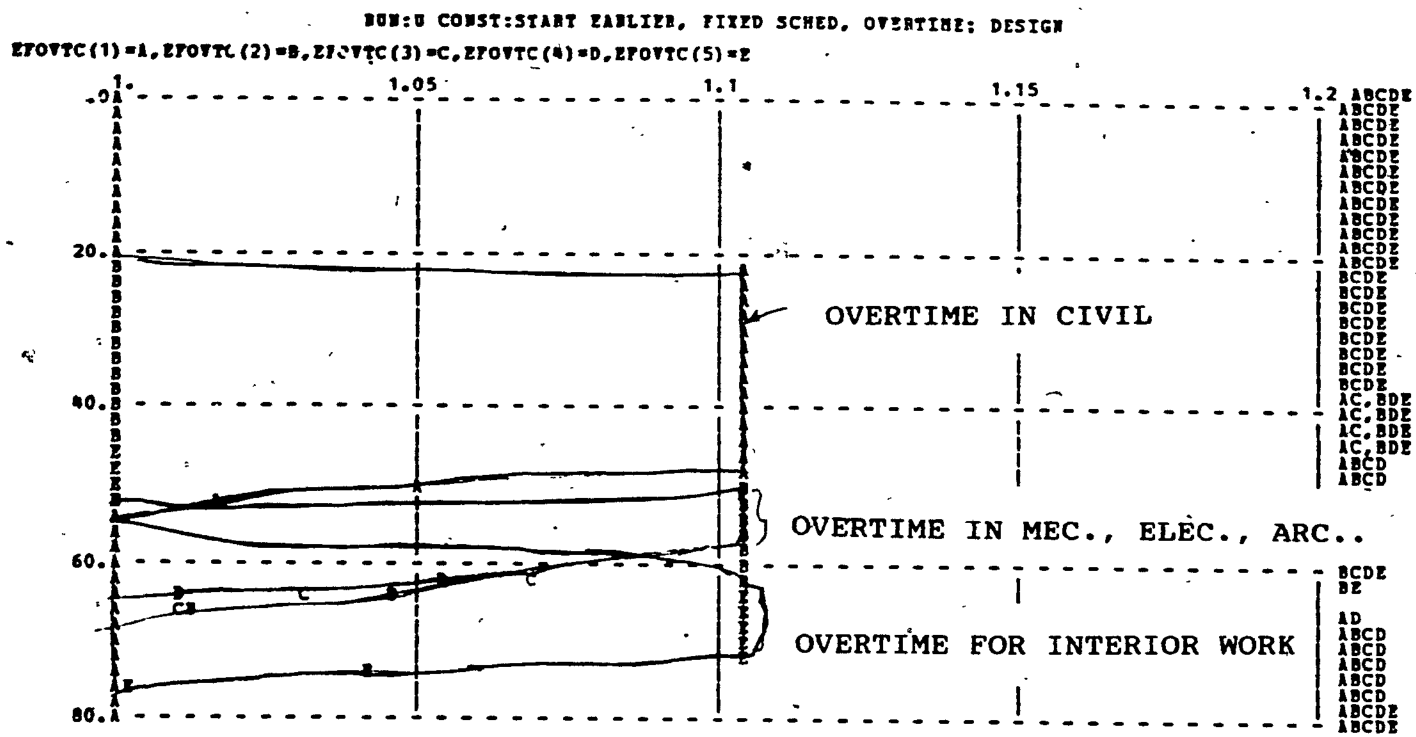


figure 106. Fast-track project; run U,
fixed construction schedule,
willingness to work on overtime
due to acceleration or schedule pressure

APPENDIX 2

LISTING OF TABULAR OUTPUTS FROM SIMULATIONS

The table presents tabular results for each specialty for these variables:

variable name	description
DSTC	determination of start time in construction
FPCOMD	fraction perceived completed in design
FCOMC	fraction perceived completed in construction
CWFDD	cumulative workforce-days in design
CCWFD	cumulative workforce-days in construction
SCDND	schedule completion date in design initially (planned)
SCDD	schedule completion date in design
SCDC	schedule completion date in construction
PW	present worth value (the project cost in constant dollars including the design , construction, procurement and financial payments).

These results are shown when the design starts and when the construction is completed (the construction completion date is also indicated). If a letter follows a result, a "T" means thousand and a "M" means million.

```
                                   RUN:B DESIGN CONSTRUCTION, CONVENTIONAL OR NO FAST-TRACK
    TIME=      .0                 CIV        MEC        ELE        ARC      INT
                      DSTD-      .000       .000       .000        0.      .000
              CIV       MEC       ELE        ARC        INT
    DSTC-     .00       .00       .00        .00        .00
              CIV       MEC       ELE        ARC        INT
  FPCOMD-    .000      .000      .000       .000       .000
              CIV       MEC       ELE        ARC        INT
  FPCOMC-   .0000     .0000     .0000       .000       .000
              CIV       MEC       ELE        ARC        INT
   CWFDD-      0.        0.        0.         0.         0.
              CIV       MEC       ELE        ARC        INT
   CCWFD-     .00       .00       .00        .00        .00
                1         2         3          4          5
   SCDND-   33.00     36.00     37.50      30.00      39.00
                1         2         3          4          5
   SCDCN-   90.00     102.0     106.0      98.00      110.0
              CIV       MEC       ELE        ARC        INT
    SCDD-   33.00     36.00     37.50      30.00      39.00
              CIV       MEC       ELE        ARC        INT
    SCDC-    90.0     102.0     106.0       98.0      110.0
      PW=     .00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    TIME=   114.0                 CIV        MEC        ELE        ARC      INT
                      DSTD-     4.000      6.000      8.000        0.     9.000
              CIV       MEC       ELE        ARC        INT
    DSTC-   50.00     72.00     66.00      72.00      85.00
              CIV       MEC       ELE        ARC        INT
  FPCOMD-   1.020     1.001     1.006      1.000      1.020
              CIV       MEC       ELE        ARC        INT
  FPCOMC-   .9960     .9734     .9727      1.004      1.014
              CIV       MEC       ELE        ARC        INT
   CWFDD-   3693.     3609.     3619.      3537.      3677.
              CIV       MEC       ELE        ARC        INT
   CCWFD-  23.93T    23.63T    22.89T     24.71T     24.56T
                1         2         3          4          5
   SCDND-   33.00     36.00     37.50      30.00      39.00
                1         2         3          4          5
   SCDCN-   90.00     102.0     106.0      98.00      110.0
              CIV       MEC       ELE        ARC        INT
    SCDD-   35.46     37.69     38.39      38.16      41.46
              CIV       MEC       ELE        ARC        INT
    SCDC-   112.8     116.5     116.5      106.6      115.8
      PW=  64.16M
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

Table 7. Base simulation (run B); conventional project

T TQC=1,1,1,1,1,1
T TOD=1,1,1,1,1,1

	TQC(1)	(2)	(3)	(4)	(5)	(6)
PRESENT	1.	1.	1.	1.	1.	1.
ORIGINAL	.99	.97	.94	.93	.96	.92

	TOD(1)	(2)	(3)	(4)	(5)	(6)
PRESENT	1.	1.	1.	1.	1.	1.
ORIGINAL	.96	.93	.93	.9	.94	.91

RUN:L GREATER QUALITY CONTROL IN DESIGN AND CONST

TIME= .0	1	2	3	4	5
DSTD-	.000	.000	.000	.000	.000
DSTC-	.00	.00	.00	.00	.00
FPCOND-	.000	.000	.000	.000	.000
FPCONC-	.000	.0000	.0000	.000	.000
RFCONC-	.000	.0000	.0000	.000	.000
CWFDD-	0.	0.	0.	0.	0.
CCWFD-	.00	.00	.00	.00	.00
SCDND-	33.00	36.00	37.50	30.00	39.00
SCDCN-	90.00	102.0	106.0	98.00	110.0
SCDD-	33.00	36.00	37.50	30.00	39.00
SCDC-	90.00	102.0	106.0	98.0	110.0
PW=	.00				

TIME= 112.0	1	2	3	4	5
DSTD-	4.000	6.000	8.000	.000	9.000
DSTC-	50.00	72.00	66.00	72.00	85.00
FPCOND-	1.017	1.007	1.009	1.005	1.017
FPCONC-	1.013	.9772	.9734	1.009	1.027
RFCONC-	1.013	.9764	.9725	1.009	1.019
CWFDD-	3199.	3153.	3173.	3185.	3181.
CCWFD-	22.31T	21.99T	21.14T	23.00T	23.22T
SCDND-	33.00	36.00	37.50	30.00	39.00
SCDCN-	90.00	102.0	106.0	98.00	110.0
SCDD-	33.54	37.28	37.87	33.62	39.28
SCDC-	95.99	115.6	115.6	100.3	114.5
PW=	59.25M				

Table 8. Conventional project (Run L): quality (QD and QC) modified

T GPRODD=.5,.5,.5,.5,.5
T GPRODC=.4,.4,.4,.4,.4

RUN R INCREASE OF THE GROSS PRODUCTIVITY

GPRODC	(1)	(2)	(3)	(4)	(5)
PRESENT	.4	.4	.4	.4	.4
ORIGINAL	.2	.2	.2	.2	.2

GPRODD	(1)	(2)	(3)	(4)	(5)
PRESENT	.5	.5	.5	.5	.5
ORIGINAL	.25	.25	.25	.25	.25

	1	2	3	4	5
TIME= .0					
DSTD-	.000	.000	.000	.000	.000
DSTC-	.00	.00	.00	.00	.00
FPCOMD-	.000	.000	.000	.000	.000
FPCOMC-	.000	.0000	.0000	.000	.000
RFCOMC-	.000	.0000	.0000	.000	.000
CWFDD-	0.	0.	0.	0.	0.
CCWFD-	.00	.00	.00	.00	.00
SCDND-	33.00	36.00	37.50	30.00	39.00
SCDCN-	90.00	102.0	106.0	98.00	110.0
SCDD-	33.00	36.00	37.50	30.00	39.00
SCDC-	90.0	102.0	106.0	98.0	110.0
PW=	.00				
TIME= 113.0					
DSTD-	4.000	6.000	8.000	.000	9.000
DSTC-	50.00	72.00	66.00	72.00	85.00
FPCOMD-	1.020	1.001	1.006	1.000	1.020
FPCOMC-	1.021	.9709	.9700	1.007	1.016
RFCOMC-	1.020	.9664	.9652	1.007	1.001
CWFDD-	1849.	1807.	1813.	1769.	1841.
CCWFD-	12.29T	11.69T	11.32T	12.32T	12.12T
SCDND-	33.00	36.00	37.50	30.00	39.00
SCDCN-	90.00	102.0	106.0	98.00	110.0
SCDD-	35.69	37.61	38.33	36.71	41.94
SCDC-	106.6	115.8	115.8	101.1	115.0
PW=	31.98M				

Table 9. Conventional project (Run R); gross productivity increased

```
T TSATD=1,1,1,1,1,1
T TSATC=1,1,1,1,1,1
```

RUN E WITH IMMEDIATE ADJUSTMENT OF SCHEDULES

	PLTPER	SAVPER				
PRESENT	4.	0.				
ORIGINAL	2.	2.				
	TSATC(1)	(2)	(3)	(4)	(5)	(6)
PRESENT	1.	1.	1.	1.	1.	1.
ORIGINAL	20.	20.	10.	6.	4.	3.
	TSATD(1)	(2)	(3)	(4)	(5)	(6)
PRESENT	1.	1.	1.	1.	1.	1.
ORIGINAL	20.	20.	12.	8.	5.	4.

TIME= .0

	1	2	3	4	5
DSTD-	.000	.000	.000	.000	.000
DSTC-	.00	.00	.00	.00	.00
FPCOMD-	.000	.000	.000	.000	.000
FPCOMC-	.0000	.0000	.0000	.0000	.0000
CWFDD-	0.	0.	0.	0.	0.
CCWFD-	.00	.00	.00	.00	.00
SCDND-	33.00	36.00	37.50	30.00	39.00
SCDCN-	90.00	102.0	106.0	98.00	110.0
SCDD-	33.00	36.00	37.50	30.00	39.00
SCDC-	90.0	102.0	106.0	98.0	110.0

PW= .00

TIME= 200.0

	1	2	3	4	5
DSTD-	4.000	6.000	8.000	.000	9.000
DSTC-	50.00	77.00	66.00	77.00	94.00
FPCOMD-	1.020	1.001	1.001	1.000	1.020
FPCOMC-	.9734	.9588	.9623	.9611	.9462
CWFDD-	3693.	3615.	3602.	3539.	3677.
CCWFD-	23.95T	24.48T	25.38T	24.87T	24.83T
SCDND-	33.00	36.00	37.50	30.00	39.00
SCDCN-	90.00	102.0	106.0	98.00	110.0
SCDD-	41.02	42.29	38.70	44.08	48.11
SCDC-	238.0	239.0	239.0	238.0	238.0

PW= 72.188

Table 10. Conventional project (Run E); immediate adjustment of the schedules

```
T TSATD=100,100,100,100,100,100
T TSATC=200,200,200,200,200,200


RUN:F   WITH FIXED-SCHEDULES POLICY

         TSATC(1)      (2)      (3)      (4)      (5)      (6)
 PRESENT     200.     200.     200.     200.     200.     200.
ORIGINAL      20.      20.      10.       6.       4.       3.

         TSATD(1)      (2)      (3)      (4)      (5)      (6)
 PRESENT     100.     100.     100.     100.     100.     100.
ORIGINAL      20.      20.      12.       8.       5.       4.

   TIME=       .0                  1        2        3         4        5
                     DSTD-      .000     .000     .000       0.     .000
                1        2         3        4        5
   DSTC-      .00      .00       .00      .00      .00
                1        2         3        4        5
 FPCOMD-     .000     .000      .000     .000     .000
                1        2         3        4        5
 FPCOMC-     .000    .0000      .000     .000     .000
                1        2         3        4        5
  CWFDD-       0.       0.        0.       0.       0.
                1        2         3        4        5
  CCWFD-      .00      .00       .00      .00      .00
                1        2         3        4        5
  SCDND-    33.00    36.00     37.50    30.00    39.00
                1        2         3        4        5
  SCDCN-    90.00    102.0     106.0    98.00    110.0
                1        2         3        4        5
   SCDD-    33.00    36.00     37.50    30.00    39.00
                1        2         3        4        5
   SCDC-    90.00    102.0     106.0    98.00    110.0
    PW=       .00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   TIME=    111.0                  1        2        3         4        5
                     DSTD-     4.000    6.000    8.000       0.    9.000
                1        2         3        4        5
   DSTC-    50.00    72.00     66.00    72.00    85.00
                1        2         3        4        5
 FPCOMD-    1.020    1.018     1.008    1.013    1.020
                1        2         3        4        5
 FPCOMC-     .997    .9870      .995    1.022    1.083
                1        2         3        4        5
  CWFDD-    3693.    3671.     3624.    3570.    3677.
                1        2         3        4        5
  CCWFD-   23.77T   24.78T    23.65T   24.86T   25.08T
                1        2         3        4        5
  SCDND-    33.00    36.00     37.50    30.00    39.00
                1        2         3        4        5
  SCDCN-    90.00    102.0     106.0    98.00    110.0
                1        2         3        4        5
   SCDD-    33.10    36.15     37.54    30.33    39.10
                1        2         3        4        5
   SCDC-    91.24    103.8     107.2    98.13    110.2
    PW=    65.18M
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

Table 11. Conventional project (Run F); fixed construction schedule

```
T TCDWF=300,300,300,300,300,300
T TSATC=2000,2000,2000,2000,2000,2000
```

	TCDWF(1)	(2)	(3)	(4)	(5)	(6)
PRESENT	300.	300.	300.	300.	300.	300.
ORIGINAL	2000.	2000.	2000.	2000.	2000.	2000.

	TSATC(1)	(2)	(3)	(4)	(5)	(6)
PRESENT	2000.	2000.	2000.	2000.	2000.	2000.
ORIGINAL	20.	20.	10.	6.	4.	3.

RUN:G DESIGNERS CEILING & FIXED-CONST. SCHEDULE

		1	2	3	4	5
TIME=	.0					
DSTD-		.000	.000	.000	.000	.000
DSTC-		.00	.00	.00	.00	.00
FPCOND-		.000	.000	.000	.000	.000
FPCONC-		.000	.000	.0000	.000	.000
CWFDD-		0.	0.	0.	0.	0.
CCWFD-		.00	.00	.00	.00	.00
SCDND-		33.00	36.00	37.50	30.00	39.00
SCDCN-		90.00	102.0	106.0	98.00	110.0
SCDD-		33.00	36.00	37.50	30.00	39.00
SCDC-		90.00	102.0	106.0	98.00	110.0
PW=	.00					
TIME=	110.0					
DSTD-		4.000	6.000	8.000	.000	9.000
DSTC-		50.00	72.00	66.00	72.00	85.00
FPCOND-		1.020	1.001	1.006	1.000	1.020
FPCONC-		.996	.984	.992	1.025	1.036
CWFDD-		3693.	3609.	3619.	3528.	3677.
CCWFD-		23.90T	25.13T	23.63T	25.19T	23.54T
SCDND-		33.00	36.00	37.50	30.00	39.00
SCDCN-		90.00	102.0	106.0	98.00	110.0
SCDD-		35.46	37.69	38.39	38.16	41.46
SCDC-		90.12	102.2	106.1	98.01	110.0
PW=	64.72M					

Table 12. Conventional project (Run G); fixed construction schedule and a ceiling on designer workforce

```
T TSATD=100,100,100,100,100,100
T TSATC=2000,2000,2000,2000,2000,2000
T TCDWF=40,40,40,40,40,40
T TCTCWF=500,500,500,500,500,500

             TCDWF(1)     (2)      (3)      (4)      (5)      (6)
   PRESENT      40.       40.      40.      40.      40.      40.
  ORIGINAL    2000.     2000.    2000.    2000.    2000.    2000.

            TCTCWF(1)     (2)      (3)      (4)      (5)      (6)
   PRESENT     500.      500.     500.     500.     500.     500.
  ORIGINAL    6000.     6000.    6000.    6000.    6000.    6000.

             TSATC(1)     (2)      (3)      (4)      (5)      (6)
   PRESENT    2000.     2000.    2000.    2000.    2000.    2000.
  ORIGINAL      20.       20.      10.       6.       4.       3.

             TSATD(1)     (2)      (3)      (4)      (5)      (6)
   PPESENT     100.      100.     100.     100.     100.     100.
  ORIGINAL      20.       20.      12.       8.       5.       4.

                              RUN:K  START EARLIER, FIXED CONST. SCHED., CEILING

     TIME=       .0
                       DSTD-    .000     .000     .000     .000     .000
     DSTC-      .00      .00      .00      .00      .00
   FPCOMD-     .000     .000     .000     .000     .000
   FPCOMC-     .000     .000    .0000     .000     .000
    CWFDD-       0.       0.       0.       0.       0.
    CCWFD-      .00      .00      .00      .00      .00
    SCDND-    33.00    36.00    37.50    30.00    39.00
    SCDCN-    90.00    102.0    106.0    98.00    110.0
     SCDD-    33.00    36.00    37.50    30.00    39.00
     SCDC-    90.00    102.0    106.0    98.00    110.0
       RW=      .00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
     TIME=    111.0
                       DSTD-   4.000    6.000    8.000     .000    9.000
     DSTC-    50.00    72.00    66.00    72.00    85.00
   FPCOMD-    1.017    1.016    1.007    1.011    1.018
   FPCOMC-     .997     .984    .9934    1.004    1.056
    CWFDD-    3663.    3663.    3622.    3554.    3670.
    CCWFD-   23.77T   25.13T   23.64T   24.41T   24.26T
    SCDND-    33.00    36.00    37.50    30.00    39.00
    SCDCN-    90.00    102.0    106.0    98.00    110.0
     SCDD-    33.18    36.23    37.65    30.40    39.16
     SCDC-    90.13    102.2    106.1    98.01    110.0
       PW=   64.77M
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

Table 13. Conventional project (Run K); fixed schedules (const and design) and a ceiling on workforce (design and const)

```
T TSATD=100,100,100,100,100,100
T TCDWF=40,40,40,40,40,40
T TSATC=2000,2000,2000,2000,2000,2000
T TWRSPD=1,1,1,1,1,1
T TWRSPC=1,1,1,1,1,1

          TCDWF(1)     (2)      (3)      (4)      (5)      (6)
PRESENT       40.      40.      40.      40.      40.      40.
ORIGINAL    2000.    2000.    2000.    2000.    2000.    2000.

          TSATC(1)     (2)      (3)      (4)      (5)      (6)
PRESENT     2000.    2000.    2000.    2000.    2000.    2000.
ORIGINAL      20.      20.      10.       6.       4.       3.

          TSATD(1)     (2)      (3)      (4)      (5)      (6)
PRESENT      100.     100.     100.     100.     100.     100.
ORIGINAL      20.      20.      12.       8.       5.       4.

         TWRSPC(1)     (2)      (3)      (4)      (5)      (6)
PRESENT        1.       1.       1.       1.       1.       1.
ORIGINAL       0.       0.       0.       1.       1.       1.

         TWRSPD(1)     (2)      (3)      (4)      (5)      (6)
PRESENT        1.       1.       1.       1.       1.       1.
ORIGINAL       0.       0.       0.       1.       1.       1.

                       RUN:J  STARTS EARLIER, FIXED CONST. SCHED., DESIGN.

   TIME=      .0                 1        2        3        4        5
                     DSTD-     .000     .000     .000     .000     .000
                         1        2        3        4        5
   DSTC-       .00      .00      .00      .00      .00
 FPCOMD-      .000     .000     .000     .000     .000
 FPCOMC-      .000     .000     .000     .000     .000
  CWFDD-        0        0        0        0        0
  CCWFD-       .00      .00      .00      .00      .00
  SCDND-     33.00    36.00    37.50    30.00    39.00
  SCDCN-     90.00    102.0    106.0    98.00    110.0
   SCDD-     33.00    36.00    37.50    30.00    39.00
   SCDC-     90.00    102.0    106.0    98.00    110.0
    PW=        .00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   TIME=     112.0               1        2        3        4        5
                     DSTD-    4.000    6.000    8.000   -1.000    9.000
                         1        2        3        4        5
   DSTC-     50.00    75.00    66.00    75.00    88.00
 FPCOMD-     1.018    1.017    1.002    1.028    1.017
 FPCOMC-      .993    1.019     .988    1.129    1.272
  CWFDD-     3832.    3871.    3807.    3814.    3869.
  CCWFD-    26.84T   28.60T   27.27T   33.74T   34.75T
  SCDND-     33.00    36.00    37.50    30.00    39.00
  SCDCN-     90.00    102.0    106.0    98.00    110.0
   SCDD-     33.38    36.43    37.82    30.47    39.34
   SCDC-     90.16    102.2    106.2    98.01    110.0
    PW=     78.57M
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

Table 14. Conventional project (Run J); fixed schedules (const and design), a ceiling on workforce in design and a willingness to recognize the schedule pressure

```
C WA=30,30,30,30,30
C T2=20,20,20,20,20
C T3=999,999,999,999,999
C DC=40,40,40,40,40
C T4=25,25,25,25,25
C T5=999,999,999,999,999
```

	DC(1)	(2)	(3)	(4)	(5)
PRESENT	40.	40.	40.	40.	40.
ORIGINAL	0.	0.	0.	0.	0.

	PLTPER	SAVPER
PRESENT	4.	0.
ORIGINAL	2.	2.

	T2(1)	(2)	(3)	(4)	(5)
PRESENT	20.	20.	20.	20.	20.
ORIGINAL	0.	0.	0.	0.	0.

	T3(1)	(2)	(3)	(4)	(5)
PRESENT	999.	999.	999.	999.	999.
ORIGINAL	999.	999.	999.	999.	999.

	T4(1)	(2)	(3)	(4)	(5)
PRESENT	25.	25.	25.	25.	25.
ORIGINAL	0.	0.	0.	0.	0.

	T5(1)	(2)	(3)	(4)	(5)
PRESENT	999.	999.	999.	999.	999.
ORIGINAL	999.	999.	999.	999.	999.

	WA(1)	(2)	(3)	(4)	(5)
PRESENT	30.	30.	30.	30.	30.
ORIGINAL	0.	0.	0.	0.	0.

RUN:H WORK ADDED AND DESIGN CHANGES

TIME= .0

	1	2	3	4	5
DSTD-	.000	.000	.000	.000	.000
DSTC-	.00	.00	.00	.00	.00
FPCOND-	.000	.000	.000	.000	.000
FPCONC-	.000	.0000	.0000	.000	.000
CWFDD-	0	0	0	0	0
CCWFD-	.00	.00	.00	.00	.00
SCDND-	33.00	36.00	37.50	30.00	39.00
SCDCN-	90.00	102.0	106.0	98.00	110.0
SCDD-	33.00	36.00	37.50	30.00	39.00
SCDC-	90.0	102.0	106.0	98.0	110.0

PW= .00

- -

TIME= 121.0

	1	2	3	4	5
DSTD-	4.000	6.000	8.000	.000	9.000
DSTC-	50.00	70.00	66.00	70.00	82.00
FPCOND-	1.007	1.000	1.002	1.033	1.007
FPCONC-	1.014	.9971	.9959	1.001	.998
CWFDD-	6371	6235	6256	7321	6242
CCWFD-	29.52	29.31	28.65	29.66	29.25
SCDND-	33.00	36.00	37.50	30.00	39.00
SCDCN-	90.00	102.0	106.0	98.00	110.0
SCDD-	34.61	42.35	39.53	36.02	42.03
SCDC-	120.6	198.7	198.7	106.0	198.5

PW= 96.95

- -

Table 15. Conventional project (Run H); work added and design change

```
T HIRDYD=1,1,1,1,1
T CHIRDY=1,1,1,1,1

        CHIRDY(1)      (2)        (3)        (4)        (5)
PRESENT       1.        1.         1.         1.         1.
ORIGINAL      2.        2.         2.         2.         2.

        HIRDYD(1)      (2)        (3)        (4)        (5)
PRESENT       1.        1.         1.         1.         1.
ORIGINAL      3.        3.         3.         3.         3.

                         RUN:0  HIRING MORE AGGRESSIVE IN DESIGN & CONST.

   TIME=       .0                 1          2          3          4          5
                      DSTD-     .000       .000       .000       .000       .000
   DSTC-      .00       .00       .00        .00        .00
 FPCOMD-     .000      .000      .000       .000       .000
 FPCOMC-     .000     .0000     .0000       .000       .000
 RFCOMC-     .000     .0000     .0000       .000       .000
  CWFDD-       0.        0.        0.         0.         0.
  CCWFD-      .00       .00       .00        .00        .00
  SCDND-    33.00     36.00     37.50      30.00      39.00
  SCDCN-    90.00     102.0     106.0      98.00      110.0
   SCDD-    33.00     36.00     37.50      30.00      39.00
   SCDC-    90.00     102.0     106.0       98.0      110.0
     PW=      .00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   TIME=    127.0                 1          2          3          4          5
                      DSTD-     4.000      6.000      8.000       .000      9.000
   DSTC-    50.00     70.00     66.00      70.00      83.00
 FPCOMD-    1.004     1.003     1.009      1.000      1.003
 FPCOMC-    1.008     .9969     .9968      1.000      1.035
 RFCOMC-    1.008     .9965     .9964      1.000      1.031
  CWFDD-    3682.     3671.     3691.      3553.      3667.
  CCWFD-   24.47T    24.45T    23.85T     24.78T     25.64T
  SCDND-    33.00     36.00     37.50      30.00      39.00
  SCDCN-    90.00     102.0     106.0      98.00      110.0
   SCDD-    33.25     37.95     38.58      39.69      39.25
   SCDC-    99.85     125.6     125.6      112.3      125.5
     PW=   67.64M
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

Table 16. Conventional project (Run 0); more aggressive to hire workers

T TWCWFD=1,1,1,1,0,0
T TWCCWF=1,1,1,1,0,0

TWCCWF	(1)	(2)	(3)	(4)	(5)	(6)
PRESENT	1.	1.	1.	1.	0.	0.
ORIGINAL	1.	1.	1.	1.	1.	1.

TWCWFD	(1)	(2)	(3)	(4)	(5)	(6)
PRESENT	1.	1.	1.	1.	0.	0.
ORIGINAL	1.	1.	1.	1.	1.	1.

RUN:M UNWILLING TO CHANGE WORKFORCE LATE

TIME= .0	1	2	3	4	5
DSTD-	.000	.000	.000	.000	.000
DSTC-	.00	.00	.00	.00	.00
FPCOMD-	.000	.000	.000	.000	.000
FPCOMC-	.000	.000	.000	.000	.000
RFCOMC-	.000	.000	.000	.000	.000
CWFDD-	0.	0.	0.	0.	0.
CCWFD-	.00	.00	.00	.00	.00
SCDND-	33.00	36.00	37.50	30.00	39.00
SCDCN-	90.00	102.0	106.0	98.00	110.0
SCDD-	33.00	36.00	37.50	30.00	39.00
SCDC-	90.00	102.0	106.0	98.00	110.0
PW=	.00				

TIME= 112.0	1	2	3	4	5
DSTD-	4.000	6.000	8.000	.000	9.000
DSTC-	50.00	72.00	66.00	72.00	85.00
FPCOMD-	1.029	1.026	1.010	1.019	1.028
FPCOMC-	1.031	1.047	1.019	1.056	1.086
RFCOMC-	1.031	1.037	1.010	1.056	1.060
CWFDD-	3735.	3717.	3640.	3615.	3718.
CCWFD-	24.83T	25.26T	23.84T	26.24T	25.55T
SCDND-	33.00	36.00	37.50	30.00	39.00
SCDCN-	90.00	102.0	106.0	98.00	110.0
SCDD-	33.09	37.05	37.41	33.19	39.08
SCDC-	91.34	111.8	111.8	99.40	111.5
PW=	66.76M				

Table 17. Conventional project (Run M); not willing to change const workers near the end of the project

T TWTRP=.9,1.1,1,1,1,1,1,1,1,1

	TWTRP(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
PRESENT	.9	1.	1.	1.	1.	1.	1.	1.	1.
ORIGINAL	0.	30.A	.1	.15	.25	.4	.55	.66	.77

	(10)	(11)
PRESENT	1.	1.
ORIGINAL	.9	1.

RUN:D WITH IMMEDIATE PERCEPTION OF REAL PROD.

TIME= .0

	1	2	3	4	5
DSTD-	.000	.000	.000	.000	.000
DSTC-	.00	.00	.00	.00	.00
FPCOMD-	.000	.000	.000	.000	.000
FPCOMC-	.0000	.0000	.0000	.000	.000
CWFDD-	0.	0.	0.	0.	0.
CCWFD-	.00	.00	.00	.00	.00
SCDND-	33.00	36.00	37.50	30.00	39.00
SCDCN-	90.00	102.0	106.0	98.00	110.0
SCDD-	33.00	36.00	37.50	30.00	39.00
SCDC-	90.0	102.0	106.0	98.0	110.0
PW=	.00				

TIME= 122.0

	1	2	3	4	5
DSTD-	3.000	6.000	8.000	.000	9.000
DSTC-	50.00	62.00	66.00	61.00	73.00
FPCOMD-	1.006	1.003	1.003	1.000	1.006
FPCOMC-	.9954	.9985	.9986	1.000	1.002
CWFDD-	3821.	3809.	3806.	3596.	3821.
CCWFD-	25.22T	24.86T	24.83T	24.79T	24.69T
SCDND-	33.00	36.00	37.50	30.00	39.00
SCDCN-	90.00	102.0	106.0	98.00	110.0
SCDD-	34.94	38.98	38.61	40.26	40.94
SCDC-	120.8	121.0	121.0	114.9	121.0
PW=	69.14M				

Table 18. Conventional project (Run D); willing to recognize the real productivity (design and const)

```
T EFESCC=.15,.15,.15,.15,.15
C EFINT=.05
```

	EFESCC(1)	(2)	(3)	(4)	(5)
PRESENT	.15	.15	.15	.15	.15
ORIGINAL	50.A	50.A	50.A	50.A	50.A

	EFINT	PLTPER	SAVPER
PRESENT	50.A	2.	0.
ORIGINAL	.1	2.	2.

RUN:P HIGH INFLATION, LOW INTEREST

TIME=	.0					
DSTD-	.000	.000	.000	.000	.000	
DSTC-	.00	.00	.00	.00	.00	
FPCOMD-	.000	.000	.000	.000	.000	
FPCOMC-	.0000	.0000	.0000	.000	.000	
CWFDD-	0.	0.	0.	0.	0.	
CCWFD-	.00	.00	.00	.00	.00	
SCDND-	33.00	36.00	37.50	30.00	39.00	
SCDCN-	90.00	102.0	106.0	98.00	110.0	
SCDD-	33.00	36.00	37.50	30.00	39.00	
SCDC-	90.0	102.0	106.0	98.0	110.0	
PW=	.00					
TIME=	114.0					
DSTD-	4.000	6.000	8.000	.000	9.000	
DSTC-	50.00	72.00	66.00	72.00	85.00	
FPCOMD-	1.020	1.001	1.006	1.003	1.020	
FPCOMC-	.9960	.9734	.9727	1.003	1.014	
CWFDD-	3693.	3609.	3619.	3528.	3677.	
CCWFD-	23.93T	23.63T	22.89T	24.71T	24.56T	
SCDND-	33.00	36.00	37.50	30.00	39.00	
SCDCN-	90.00	102.0	106.0	98.00	110.0	
SCDD-	35.46	37.69	38.39	38.16	41.46	
SCDC-	112.8	116.5	116.5	106.6	115.8	
PW=	79.39M					

Table 19. Conventional project (Run P);
inflation rate: 15%
interest rate: 5%

```
C CONSST=25
C PROCST=20.20,20,20,20
```

	CONSST	PLTPER			
PRESENT	25.	2.			
ORIGINAL	50.	2.			
	PROCST(1)	(2)	(3)	(4)	(5)
PRESENT	20.	20.	20.	20.	20.
ORIGINAL	45.	45.	45.	45.	45.

RUN:C DESIGN CONSTRUCTION WITH FAST TRACK

TIME=	.00					
DSTD-	1 .000	2 .000	3 .000	4 .000	5 .000	
DSTC-	1 .00	2 .00	3 .00	4 .00	5 .00	
FPCOMD-	1 .000	2 .000	3 .000	4 .000	5 .000	
FPCOMC-	1 .0000	2 .0000	3 .0000	4 .000	5 .000	
CWFDD-	1 0.	2 0.	3 0.	4 0.	5 0.	
CCWFD-	1 .00	2 .00	3 .00	4 .00	5 .00	
SCDND-	1 33.00	2 36.00	3 37.50	4 30.00	5 39.00	
SCDCN-	1 65.00	2 77.00	3 81.00	4 73.00	5 85.00	
SCDD-	1 33.00	2 36.00	3 37.50	4 30.00	5 39.00	
SCDC-	1 65.00	2 77.00	3 81.00	4 73.00	5 85.00	
PW=	.00					
TIME=	89.00					
DSTD-	1 4.000	2 6.000	3 8.000	4 .000	5 9.000	
DSTC-	1 25.00	2 49.00	3 41.00	4 49.00	5 62.00	
FPCOMD-	1 1.020	2 1.001	3 1.006	4 1.000	5 1.020	
FPCOMC-	1 .9954	2 .9683	3 .9659	4 1.004	5 1.017	
CWFDD-	1 3693.	2 3609.	3 3619.	4 3528.	5 3677.	
CCWFD-	1 24.95T	2 23.61T	3 22.71T	4 24.78T	5 24.59T	
SCDND-	1 33.00	2 36.00	3 37.50	4 30.00	5 39.00	
SCDCN-	1 65.00	2 77.00	3 81.00	4 73.00	5 85.00	
SCDD-	1 35.46	2 37.69	3 38.39	4 38.16	5 41.46	
SCDC-	1 87.66	2 92.11	3 92.15	4 76.65	5 91.22	
PW=	65.46M					

Table 20. Fast-track project; run C

```
T EFESCC=.15,.15,.15,.15,.15
C EFINT=.05
C PROCST=20,20,20,20,20

           EFESCC(1)      (2)       (3)       (4)       (5)
PRESENT        .15        .15       .15       .15       .15
ORIGINAL      50.A       50.A      50.A      50.A      50.A

              EFINT    PLTPER
PRESENT       50.A       2.
ORIGINAL        .1       2.

           PROCST(1)      (2)       (3)       (4)       (5)
PRESENT        20.        20.       20.       20.       20.
ORIGINAL       45.        45.       45.       45.       45.

              SAVPER
PRESENT         0.
ORIGINAL        2.

                          RUN:W   START CONST EARLIER, HIGH INFLATION, LOW INTEREST

    TIME=      .00
                        DSTD-     .000      .000      .000      .000      .000
    DSTC-      .00       .00       .00       .00       .00
  FPCOMD-     .000      .000      .000      .000      .000
  FPCOMC-    .0000     .0000     .0000      .000      .000
   CWFDD-       0.        0.        0.        0.        0.
   CCWFD-      .00       .00       .00       .00       .00
   SCDND-    33.00     36.00     37.50     30.00     39.00
   SCDCN-    65.00     77.00     81.00     73.00     85.00
    SCDD-    33.00     36.00     37.50     30.00     39.00
    SCDC-    65.00     77.00     81.00     73.00     85.00
      PW=      .00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    TIME=    89.00
                        DSTD-    4.000     6.000     8.000      .000     9.000
    DSTC-    25.00     49.00     41.00     49.00     62.00
  FPCOMD-    1.020     1.001     1.006     1.000     1.020
  FPCOMC-    .9954     .9683     .9659     1.004     1.017
   CWFDD-    3693.     3609.     3619.     3528.     3677.
   CCWFD-   24.95T    23.61T    22.71T    24.78T    24.59T
   SCDND-    33.00     36.00     37.50     30.00     39.00
   SCDCN-    65.00     77.00     81.00     73.00     85.00
    SCDD-    35.46     37.69     38.39     38.16     41.46
    SCDC-    87.66     92.11     92.15     76.65     91.22
      PW=   76.47M
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

Table 21. **Fast-track project; run W inflation rate:15%, interest rate:5%**

```
              C CONSST=20
              C PROCST=15,15,15,15,15
              T NOVSPC=1,1,1,1,1
              T NOVRTA=1,1,1,1,1
              T TSATC=2000,2000,2000,2000,2000,2000
              T TCDWF=40,40,40,40,40,40
            PROCST(1)       (2)       (3)       (4)       (5)
   PRESENT      15.        15.       15.       15.       15.
  ORIGINAL      45.        45.       45.       45.       45.

              SAVPER
   PRESENT       0.
  ORIGINAL       2.

             TCDWF(1)       (2)       (3)       (4)       (5)       (6)
   PRESENT      40.        40.       40.       40.       40.       40.
  ORIGINAL    2000.      2000.     2000.     2000.     2000.     2000.

             TSATC(1)       (2)       (3)       (4)       (5)       (6)
   PRESENT    2000.      2000.     2000.     2000.     2000.     2000.
  ORIGINAL      20.        20.       10.        6.        4.        3.

            NOVRTA(1)       (2)       (3)       (4)       (5)
   PRESENT       1.         1.        1.        1.        1.
  ORIGINAL       0.         0.        0.        0.        0.

            NOVSPC(1)       (2)       (3)       (4)       (5)
   PRESENT       1.         1.        1.        1.        1.
  ORIGINAL       0.         0.        0.        0.        0.

                            RUN:U CONST:START EARLIER, FIXED SCHED, OVERTIME; DESI

    TIME=       .00                  1          2          3          4          5
                          DSTD-    .000       .000       .000       .000       .000
     DSTC-      .00        .00      .00        .00        .00
   FPCOND-     .000       .000     .000       .000       .000
   FPCONC-     .000       .000    .0000       .000       .000
   RFCONC-    .0000      .0000    .0000       .000       .000
    CWFDD-       0.         0.       0.         0.         0.
    CCWFD-      .00        .00      .00        .00        .00
    SCDND-    33.00      36.00    37.50      30.00      39.00
    SCDCN-    60.00      72.00    76.00      68.00      80.00
     SCDD-    33.00      36.00    37.50      30.00      39.00
     SCDC-    60.00      72.00    76.00      68.00      80.00
       PW=      .00
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    TIME=     81.00                  1          2          3          4          5
                          DSTD-   4.000      6.000      8.000       .000      9.000
     DSTC-    20.00      44.00    36.00      44.00      55.00
   FPCOND-    1.005      1.005    1.014      1.000      1.007
   FPCONC-     .994       .986    .9913      1.018      1.058
   RFCONC-    .9944      .9850    .9891      1.018      1.035
    CWFDD-    3621.      3611.    3657.      3533.      3613.
    CCWFD-   27.84T     26.74T   25.27T     26.65T     26.25T
    SCDND-    33.00      36.00    37.50      30.00      39.00
    SCDCN-    60.00      72.00    76.00      68.00      80.00
     SCDD-    34.30      38.47    39.47      37.18      40.24
     SCDC-    60.14      72.19    76.14      68.01      80.03
       PW=   110.68
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

Table 22. Fast-track project; run U, fixed construction schedule, willingness to work on overtime due to acceleration or schedule pressure

DESCRIPTION OF STRATEGY	RUN NO	Table No	Design Finish Time planned	Design Finish Time actual	Const. Start Time	Proc. Start Time	Const. Finish Time planned	Const. Finish Time actual	Total Cost	Total man-days
			(week)	(week)	(week)	(week)	(week)	(week)	(million) (constant$)	(man-days) (X1000)
Conventional (base run) design completed before const. start	B	7	39	42	50	45	110	114	64,2	137,8
Fast-track (construction starts before the end of design	C	20	39	42	25	20	85	89	65,5	138,8
OTHER STRATEGIES:										
Conventional; and willingness to recognize soon the real productivity	D	18	39	41	50	45	110	122	69,7	143,2
Conventional; and immediate adjustement of schedule	E	10	39	42	50	45	110	238	72,2	141,6
Conventional; with fixed schedule	F	11	39	42	50	45	110	111	65,2	140,4
Conventional; and ceiling on designers, const fixed schedule	G	12	39	42	50	45	110	110	64,7	139,5
Conventional; work added and design change	H	15	39	42	50	45	85	113	97,0	178,8

(see note on the following page)

TABLE 23. Summary of Results

DESCRIPTION OF STRATEGY	RUN NO	Table No	Design Finish Time planned (week)	Design Finish Time actual (week)	Const. Start Time (week)	Proc. Start Time (week)	Const. Finish Time planned (week)	Const. Finish Time actual (week)	Total Cost (million) (constant$)	Total man-days (man-days) (X1000)
Conventional; ceiling on design workers and fixed const schedule and willing to recognize the schedule pressure	J	14	39	39	50	45	110	112	78.6	170.4
Conventional; ceiling design & const & fixed design &const schedule	K	13	39	39	50	45	110	111	64.8	139.4
Conventional; greater quality control	L	8	39	39	50	45	110	112	59.3	127.6
Conventional; not willing to change workforce late	M	17	39	39	50	45	110	121	66.8	144.2
Conventional; agressive hiring	O	16	39	40	50	45	110	127	67.6	141.4
Conventional; inflation 15% interest 5%	P	19	39	42	50	45	110	114	79.4	137.9
Conventional; double gross productivity	R	9	39	42	50	45	110	113	32.0	68.8
Fast-track; fixed const schedule, designer ceiling and willing for overtime	U	22	39	40	20	15	80	81	118.6	150.8
Fast-track; inflation 15% interest 5%	W	21	39	42	25	20	85	89	76.5	138.8

note: see next page for definitions

TABLE 23. Summary of Results

The table 23 presents a summary of results of major variables of selected simulations done on the main frame computer at the Ecole Polytechnique; a reference is also included for the tabular or the graphical results presented in the previous pages.

The factors described are the values (constant or table) given by the modeler before to run the model:

1. the procurement start time; it is assumed that the procurement starts after the owner awards the contract
2. the construction start time; it is assumed that the construction on site starts five weeks after the award due to the planning period for coordination, procurement and to award subcontractors contracts
3. the design finish date; the design duration for each specialty is set to 30 working weeks by the modeler; the total time to complete the design is greater than these 30 working weeks because, for each timestep, the model revises the schedule completion date for each specialty in taking into account the interrelations between the specialties to start, to progress or to finish the design. The total duration expected initially is 39 working weeks; the real total duration is the gap between the design end and the design start.

4. the construction finish date; the construction duration is set by the modeler to 40 working weeks for each specialty; as it is for the design, due to the interrelations between the specialties, the model calculates for the each specialty (excepted for the civil work which is specified by the modeler) the start date and the end date. So the total duration is the gap between the start date of civil work and the latest end date of construction work.
5. The total cost includes the design cost, the construction cost, the material cost, the financial payment during the design and construction processes. The cost is in constant dollars to be able to compare other policies: in a simulation, the cost in constant dollars is escalated due to the inflation rate; these actual dollars are transferred in constant dollars in relation with the interest rate.
6. In order to understand how to apply a a specific strategy, the equations modified are described in the tables for tabular outputs.

APPENDIX 3

LISTING OF EQUATIONS

Listing of the Equations

Before to list the equations, the definition of equations in a matrix must be explained: if the expression (DI) is in the equation, (DI) means the civil, mechanical, architectural (exterior work) and interior specialties; each equation is a matrix, meaning that the equation is related to the five specialties. The equations that are not with the parameter "DI" are related to a specific specialty: to acheive this, the parameter "DI3" means the mechanical specialty; so, the following parameters can define the other specialties to indicate interrelations between the specialties:

```
(DI3-1): for the civil specialty
  (DI3): for the mechanical speciqalty
(DI3+1): for the electrical specialty
(DI3+2): for the architectural specialty (exterior
         work)
(DI3+3): for the interior specialty (interior
         architecture)
```

DESIGN SUBSYSTEM

```
A QD.K(DI)=SMOOTH((TABHL(TQD,FPCOMD.K(DI),0,1,.2)
                -EWAQD.K(DI))*WEQD.K(DI)*SCPEQD.K(DI)
                  ,QDEL(DI))
          QUALITY OF DESIGN (DIMENSIONLESS)
T TQD=.96,.93,.93,.90,.94,.91
          TABLE FOR QUALITY OF DESIGN (DIMENSIONLESS)
P QDEL=5,5,5,5,5
          QUALITY DELAY (WORKING WEEK)
A EWAQD.K(DI)=TABHL(TEWAQD,FPCOMD.K(DI),0,1,.2)
       *SWITCH(0,1,NWAR.K(DI))*(1-DQMWA.K(DI))
```

```
          EFFECT OF WORK ADDED ON QUALITY IN DESIGN
           (DIMENSIONLESS)
T TEWAQD=0,0,.2,.4,.65,1
          TABLE OF EFFECT OF WORK ADDED ON QUALITY
           IN DESIGN (DIMENSIONLESS)
A WEQD.K(DI)=TABHL(TWEQ,WFQFD.K(DI),0,1,.2)
          WORKFORCE WITH EXPERIENCE ON QUALITY IN
           DESIGN(DIMENSIONLESS)
T TWEQ=.91,.94,.96,.98,.99,1
          TABLE FOR WORKFORCE WITH EXPERIENCE EFFECT
           ON QUALITY (DIMENSIONLESS)
A WFQFD.K(DI)=WFEXPD.K(DI)/(TDWF.K(DI)+1)
          WORKFORCE QUALITY FACTOR IN DESIGN
           (DIMENSIONLESS)
A SCPEQD.K(DI)=(TABHL(TSCPEQ,RCPPPD.K(DI),1,2,.25)*
             WRSPD.K(DI))+(1-WRSPD.K(DI))
          SCHEDULE PRESSURE EFFECT ON QUALITY ON
           DESIGN
T TSCPEQ=1,.95,.9,.98,.98
          TABLE FOR SCHEDULE PRESSURE ON QUALITY
           (DIMENSIONLESS)
A DQMWA.K(DI)=TABHL(TDQMWA,RWATW.K(DI),0,1,.2)
          DESIGN QUALITY MULTIPLIER DUE TO THE RATIO
           OF WORK ADDED (DIMENSIONLESS)
T TDQMWA=1,.98,.95,.91,.86,.8
          TABLE FOR DESIGN QUALITY MULTIPLIER DUE TO
           WORK ADDED (DIMENSIONLESS)
A RWATW.K(DI)=TWA.K(DI)/IW(DI)
          RATIO OF WORK ADDED TO TOTAL WORK IN DESIGN
           (DIMENSIONLESS)
C IW=150,150,150,150,150
          INITIAL WORK IN DESIGN (DRAWING)
A TWA.K(DI)=WAAPD.K(DI)+WANAPD.K(DI)
          TOTAL WORK ADDED (DRAWINGS)
A NWAR.K(DI)=WARAD.JK(DI)
          NOTICE OF WORK ADDED RATE TO AFFECT THE
           DESIGN QUALITY (DRAWING/WEEK)

A RCPPPD.K(DI)=
         SWITCH(1,CAPRGD.K(DI)/MAX(FPCOMD.K(DI),.01),
                                    FPCOMD.K(DI))
          RATIO OF CALIBRATED PROGRESS TO PERCEIVED
           PROGRESS IN DESIGN (DIMENSIONLESS)
A CAPRGD.K(DI)=TABHL(TCAPRD,PRGRD.K(DI),0,1,.1)
T TCAPRD=0,.04,.07,.12,.20,.35,.47,.6,.7,.85,1
          CALIBRATED PROGRESS IN DESIGN
T TCAPRD=0,.04,.07,.12,.20,.35,.47,.6,.7,.85,1
          TABLE FOR CALIBRATED PROGRESS IN DESIGN
           (DIMENSIONLESS)
```

```
A PRGRD.K(DI)=
      SWITCH(1,CLIP(1,(TIME.K-DSTD.K(DI))/
                  SCDD.K(DI)-DSTD.K(DI)),
         FPCOMD.K(DI),1),FPCOMD.K(DI))
        PROGRESS RATIO IN DESIGN (DIMENSIONLESS)
L DSTD.K(DI)=DSTD.J(DI)+DT*(DSDD.J(DI)*(1/DT))
N DSTD(DI)=0
        DETERMINATION OF START TIMES IN DESIGN
         (WEEK)
A DSDD.K(DI)=(TIME.K-(3*DT))*
              CLIP(1,0,FLAGRD.JK(DI)*DT,1)
        DETERMINATION OF START DATES IN DESIGN
         (WEEK)
R FLAGRD.KL(DI)=SWITCH(0,1,FPCOMD.K(DI))*
               CLIP(0,1,FLAGDS.K(DI),1)/DT
        FLAG RATE IN DESIGN TO DETERMINE START DATES
         IN DESIGN ("FLAG"/WEEK)
L FLAGDS.K(DI)=FLAGDS.J(DI)+DT*(FLAGRD.JK(DI))
N FLAGDS(DI)=0
        FLAG IN DESIGN FOR START DATES ("FLAG")
L SQD.K(DI)=SQD.J(DI)+DT*QDGN.J(DI)
N SQD(DI)=QD(DI)
        SUM OF QUALITY DESIGN (DIMENSIONLESS)
A QDGN.K(DI)=SWITCH(0,CLIP(0,QD.K(DI),FPCOMD.K(DI),1),
                  FPCOMD.K(DI))
        QUALITY OF DESIGN TO DETERMINE THE QUALITY
         OF SHOP DRAWINGS (DIMENSIONLESS)
A AVQD.K(DI)=SQD.K(DI)/CLIP(SCDD.K(DI)-DSTD.K(DI),
                  MAX(TIME.K-DSTD.K(DI),1),
                          FPCOMD.K(DI),1)
        AVERAGE QUALITY OF DESIGN (DIMENSIONLESS)
A CPPRGD.K(DI)=DNNR.K(DI)+UDNR.K(DI)
        CUMULATIVE PERCEIVED PROGRESS IN DESIGN
         (DRAWING)
A FPCOMD.K(DI)=CPPRGD.K(DI)/(IW(DI)+TWA.K(DI))+UDR.K
          (DI)+DTRWAD.K(DI)+DRDC.K(DI)
        FRACTION PERCEIVED COMPLETE IN DESIGN
         (DIMENSIONLESS)
A DEPREM.K(DI)=(IW(DI)+TWA.K(DI)+UDR.K(DI)+DTRWAD.K(DI)
           +DRDC.K(DI)-CPPRGD.K(DI))/
        SWITCH(GPRODD(DI),DPPROD.K(DI),FPCOMD.K(DI))
C GPRODD=.25/.25/.25/.25/.25
        GROSS PRODUCTIVITY IN DESIGN
         (DRAWING/MAN-WEEK)
A DPPROD.K(DI)=SMOOTH(IPRODD.K(DI),TPPROD(DI))
        DESIGN PERCEIVED PRODUCTIVITY
         (DRAWING/PERSON-WEEK)
P TPPROD=4,4,4,4,4
        TIME TO PERCEIVED PRODUCTIVITY IN DESIGN
         (WORKING WEEKS)
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```
A IPRODD.K(DI)=(WTRPD.K(DI)*DRPROD.K(DI))+
         (1-WTRPD.K(DI))*GPRODD(DI)

         INDICATED PRODUCTIVITY IN DESIGN
          (DRAWING/PERSON-WEEK)

A DRPROD.K(DI)=
          CLIP(DNNR.K(DI)/((CWFDD.K(DI)+1)/NBERDW),
     DNNRP.K(DI)/((WFEXPD.K(DI)+WFNEWD.K(DI)+1)*DT),
                                   FPCOMD.K(DI),.99)
         DESIGN REAL PRODUCTIVITY
          (DRAWING/PERSON-WEEK)
C NBERDW=5
         NUMBER OF DAYS PER WEEK (WORKING DAYS/WEEK)

L DNNRP.K(DI)=DNNRP.J(DI)+DT*(RDNNR.JK(DI)-
                              RDNNR2.JK(DI))
N DNNRP(DI)=0
         DESIGN NOT NEEDING REWORK TO FIND THE REAL
          PRODUCTIVITY (DRAWING)
R RDNNR2.KL(DI)=DNNRP.K(DI)/DT
         RATE OF DRAWINGS NOT NEEDING REWORK #2 (AT
          TIME.K-DT) TO FIND THE REAL PRODUCTIVITY
          (DRAWING/WEEK)
A WTRPD.K(DI)=TABHL(TWTRP,FPCOMD.K(DI),0,1,.1)
         WILLINGNESS TO TAKE THE REAL PRODUCTIVITY
          (DIMENSIONLESS)
T TWTRP=0,.03,.1,.15,.25,.4,.55,.66,.77,.9,1
         TABLE FOR WILLINGNESS TO TAKE THE REAL
          PRODUCTIVITY (DIMENSIONLESS)
A TPREQD.K(DI)=SWITCH(DURDN(DI),
    DEPREM.K(DI)*RTRAFD.K(DI)/MAX(DWFS.K(DI),1),
              FPCOMD.K(DI))
         TIME PERCEIVED REQUIRED IN DESIGN (WEEK)
C DURDN=30,30,30,30,30
         DURATION OF SPECIALTIES: IN DESIGN INITIALLY
          (WEEK)
A RTRAFD.K(DI)=TABHL(TRTRFD,FPCOMD.K(DI),0,1,.1)
         REQUIRED TRAPEZOIDAL FACTOR IN DESIGN
          (DIMENSIONLESS)
T TRTRFD=.29,.78,1.32,1.45,1.52,1.47,1.42,1.37,
    1.24,1.11,.48
         TABLE FOR THE REQUIRED TRAPEZOIDAL FACTOR IN
          DESIGN (DIMENSIONLESS)
A ICDD.K(DI3-1)=
     CLIP(SCDD.K(DI3-1),
         SWITCH(SCDND.K(DI3-1),
                TIME.K+MAX(TPREQD.K(DI3-1),
                        (TPREQD.K(DI3+2)*CPCDCA)),
                         FPCOMD.K(DI3-1)),
         FPCOMD.K(DI3-1),1)
```

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         INDICATED COMPLETION DATE (WEEK)
C CPCDCA=.4
         COMPLETION PERCENTAGE OF CIVIL DESIGN
          COMPARED TO ARCHITECTURAL DESIGN
          (DIMENSIONLESS)
A ICDD.K(DI3)=
      CLIP(SCDD.K(DI3),
          SWITCH(SCDND.K(DI3),
                 TIME.K+MAX(TPREQD.K(DI3),
                        MAX(TPREQD.K(DI3+1)*.7,
                            TPREQD.K(DI3+3)*.7),
                            FPCOMD.K(DI3)),
           FPCOMD.K(DI3),1)
         INDICATED COMPLETION DATE FOR MECHANICAL
          DESIGN (WEEK)
A ICDD.K(DI3+1)=
      CLIP(SCDD.K(DI3+1),
          SWITCH(SCDND.K(DI3+1),
                 TIME.K+MAX(TPREQD.K(DI3+1),
                        MAX(TPREQD.K(DI3)*.7,
                            TPREQD.K(DI3+3)*.7),
                            FPCOMD.K(DI3+1)),
         FPCOMD.K(DI3+1),1)
         INDICATED COMPLETION DATE FOR ELEC DESIGN
          (WEEK)
A ICDD.K(DI3+2)=
      CLIP(SCDD.K(DI3+2),
          SWITCH(SCDND.K(DI3+2),
               TIME.K+MAX(TPREQD.K(DI3+2),
                      MAX(TPREQD.K(DI3-1)*.6,
                     MAX((TPREQD.K(DI3))*CPADCM,
                          TPREQD.K(DI3+1)*CPADCE))),
                          FPCOMD.K(DI3+2)),
          FPCOMD.K(DI3+2),1)
         INDICATED COMPLETION DATE FOR ARCHITECTURAL
          DESIGN (WEEK)
C CPADCM=.6
         COMPLETION PERCENTAGE OF ARCHITECTURAL
          DESIGN COMPARED TO MECHANICAL DESIGN
          (DIMENSIONLESS)
C CPADCE=.6
         COMPLETION PERCENTAGE OF ARCHITECTURAL
          DESIGN COMPARED TO ELECTRICAL DESIGN
          (DIMENSIONLESS)
A ICDD.K(DI3+3)=
      CLIP(SCDD.K(DI3-1),
          SWITCH(SCDND.K(DI3+3),
                 TIME.K+MAX(TPREQD.K(DI3+3),
                        MAX(TPREQD.K(DI3)*.8,
                            TPREQD.K(DI3+1)*.8),
                            FPCOMD.K(DI3+3)),
          FPCOMD.K(DI3+3),1)
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            INDICATED COMPLETION DATE FOR INTERIOR
             DESIGN (WEEK)

L SCDD.K(DI)=SCDD.J(DI)+DT*NASD.JK(DI)
N SCDD(DI)=SCDND(DI)
            SCHEDULE COMPLETION DATE IN DESIGN (WEEK)
A SCDND.K(DI3-1)=(DURDN(DI3+2)*PPABCD)+DURDN(DI3-1)
            SCHEDULE COMPLETION DATE INITIALLY IN DESIGN
             (WEEK)
C PPABCD=.1
            PERCENTAGE OF PROGRESS OF ARCHITECTURAL
             BEFORE CIVIL DESIGN (DIMENSIONLESS)
A SCDND.K(DI3)=(DURDN(DI3+2)*PPABMD)+DURDN(DI3)
            SCHEDULE COMPLETION DATE INITIALLY IN DESIGN
             (WEEK)
C PPABMD=.2
            PERCENTAGE OF PROGRESS OF ARCHITECTURAL
             BEFORE MECHANICAL DESIGN (DIMENSIONLESS)
A SCDND.K(DI3+1)=(DURDN(DI3+2)*PPABED)+DURDN(DI3+1)
            SCHEDULE COMPLETION DATE INITIALLY IN DESIGN
             (WEEK)
C PPABED=.25
            PERCENTAGE OF PROGRESS OF ARCHITECTURAL
             BEFORE ELECTRICAL DESIGN (DIMENSIONLESS)
A SCDND.K(DI3+2)=DURDN(DI3+2)
            SCHEDULE COMPLETION DATE INITIALLY IN DESIGN
             (WEEK)
A SCDND.K(DI3+3)=(DURDN(DI3+2)*PPABID)+DURDN(DI3+3)
            SCHEDULE COMPLETION DATE INITIALLY IN DESIGN
             (WEEK)
C PPABID=.3
            PERCENTAGE OF PROGRESS OF ARCHITECTURAL
             BEFORE INTERIOR DESIGN (DIMENSIONLESS)
R NASD.KL(DI)=(ICDD.K(DI)-SCDD.K(DI))/SATD.K(DI)*
                  CLIP(0,1,FPCOMD.K(DI),1)
            NET ADDITION TO SCHEDULE IN DESIGN
             (WEEK/WEEK)
A SATD.K(DI)=TABHL(TSATD,FPCOMD.K(DI),0,1,.2)
            SCHEDULE ADJUSTEMENT TIME IN DESIGN (WEEK)
T TSATD=20,20,12,8,5,4
            TABLE FOR SCHEDULE ADJUSTMENT TIME IN DESIGN
             (WEEK)
A TREMD.K(DI)=
        SWITCH(DURDN(DI),SCDD.K(DI)-TIME.K,FPCOMD.K(DI))
                         *CLIP(0,1,FPCOMD.K(DI),1)
            TIME REMAINING IN DESIGN (WORKING WEEK)
R RUDNR.KL(DI)=APPRGD.K(DI)*(1-QD.K(DI))
            RATE OF UNDISCOVERED DESIGN NEEDING REWORK
             (DRAWING/WEEK)
L UDNR.K(DI)=UDNR.J(DI)+DT*(RUDNR.JK(DI)-RDUDNR.JK(DI))
N UDNR(DI)=0
            UNDISCOVERED DESIGN NEEDING REWORK (DRAWING)
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R RDUDNR.KL(DI)=UDNR.K(DI)/TDRW.K(DI)
            RATE OF DETECTION OF UNDISCOVERED DESIGN
             NEEDING REWORK (DRAWING/WEEK)
A TDRW.K(DI)=TABHL(TTDRW,FPCOMD.K(DI),0,1,.1)
            TIME TO DETECT REWORK (WEEK)
T TTDRW=10,10,9,8,7,6,5,4,3,3,3
            TABLE FOR TIME TO DETECT REWORK (WEEK)
L DNNR.K(DI)=DNNR.J(DI)+DT*(RDNNR.JK(DI)-DTRWA.JK(DI)
                            -DTRDC.JK(DI))
N DNNR(DI)=0
            DRAWING NOT NEEDING REWORK (CUMULATIVE REAL
             PROGRESS) (DRAWING)
R RDNNR.KL(DI)=APPRGD.K(DI)*QD.K(DI)
            RATE OF DRAWINGS NOT NEEDIND REWORK
             (DRAWING/WEEK)

R DTRWA.KL(DI)=(TWA.K(DI)-WANAPD.K(DI)-DTRWAD. K(DI))/
                 TDDR(DI)
            DESIGN TO REWORK DUE TO WORK ADDED IN DESIGN
             (DRAWING/WEEK)
P TDDR=2,2,2,2,2
            TIME TO DETECT REWORK (ON GOOD DESIGN)
             (WEEKS)
L DTRWAD.K(DI)=DTRWAD.J(DI)+DT*DTRWA.JK(DI)
N DTRWAD(DI)=0
            DRAWINGS TO REWORK DUE TO WORK ADDED IN
             DESIGN (DRAWING)
R DTRDC.KL(DI)=PULSE(DC(DI)/DT,T4(DI),T5(DI))
            RATE OF DRAWINGS TO REWORK DUE TO DRAWING
             CHANGED (DRAWING/WEEK)
C DC=0,0,0,0,0
            DESIGN CHANGE (DRAWING)
C T4=20,20,20,20,20
            TIME TO START THE DESIGN CHANGED (WEEK)
C T5=30,30,30,30,30
            INTERVAL TIME TO DESIGN CHANGED (WEEK)
A APPRGD.K(DI)=TDWF.K(DI)*APRODD.K(DI)
            APPARENT PROGRESS IN DESIGN (DRAWING/WEEK)
L WAAPD.K(DI)=WAAPD.J(DI)+DT*WARAD.JK(DI)
N WAAPD(DI)=0
            WORK ADDED AFFECTING PROGRESS IN DESIGN
             (DRAWING)
R WARAD.KL(DI)=PULSE(WA(DI)/DT,T2(DI),T3(DI))*
                      (1-PWANAD.K(DI))
            WORK ADDED RATE AFFECTING THE DESIGN
             (DRAWING/WEEK)
C WA=0,0,0,0,0
            WORK ADDED IN DESIGN (DRAWING)
C T2=0,0,0,0,0
            TIME TO START THE WORK ADDED (WEEK)
C T3=999,999,999,999,999
            INTERVAL TIME TO ADD WORK (WEEK)
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R WARNAD.KL(DI)=PULSE(WA(DI)/DT,T2(DI),T3(DI))*
                                         PWANAD.K(DI)
           WORK ADDED RATE NOT AFFECTING THE DESIGN
            (DRAWING/WEEK)
A PWANAD.K(DI)=TABHL(TPWANA,FPCOMD.K(DI),0,1,.2)
           PERCENTAGE OF WORK ADDED NOT AFFECTING THE
            DESIGN (DIMENSIONLESS)
T TPWANA=1,.95,.9,.85,.8,.75
           TABLE FOR THE PERCENTAGE OF WORK ADDED NOT
            AFFECTING THE DESIGN (DIMENSIONLESS)
L WANAPD.K(DI)=WANAPD.J(DI)+DT*WARNAD.JK(DI)
N WANAPD(DI)=0
           WORK ADDED NOT AFFECTING PROGRESS IN
            DESIGN (DRAWING)
A SCPEPD.K(DI)=(TABHL(TSPEP,RCPPPD.K(DI),.75,2,.25)
           *(WRSPD.K(DI))+(1-WRSPD.K(DI))
           SCHEDULE PRESSURE EFFECT ON PRODUCTIVITY IN
            DESIGN (DIMENSIONLESS)
T TSPEP=.9,.98,1.15,1.2,.9,.8
           TABLE FOR THE SCHEDULE PRESSURE EFFECT ON
            PRODUCTIVITY (DIMENSIONLESS)
A APRODD.K(DI)=GPRODD(DI)*EFJSD.K(DI)*LEPROD.K(DI)
            *SCPEPD.K(DI)*FIWFD.K(DI)
           APPARENT PRODUCTIVITY IN DESIGN
            (DRAWING/PERSON-WEEK)
A EFJSD.K(DI)=TABHL(TEFJSD,TPDMD.K(DI)*NBRHDD(DI),
                       0,1000000,200000)
           EFFECT OF JOB SIZE ON DESIGN PRODUCTIVITY
            (DIMENSIONLESS)
T TEFJSD=1.06,1.01,.99,.97,.95,.92
           TABLE FOR THE EFFECT OF JOB SIZE IN DESIGN
            (DIMENSIONLESS)
C NBRHDD=8,8,8,8,8
           NUMBER OF HOURS PER DAY IN DESIGN
            (HOURS/DAY)
A LEPROD.K(DI)=TABHL(TLEPD,FPCOMD.K(DI),0,1,.2)
                              -RLOPPD.K(DI)
           LEARNING EFFECT ON PRODUCTIVITY IN DESIGN
            (DIMENSIONLESS)
T TLEPD=.93,.97,1.03,1.06,1.07,1.09
           TABLE FOR LEARNING EFFECT ON PRODUCTIVITY
            (DIMENSIONLESS)
A RLOPPD.K(DI)=
   CLIP(SMOOTH(.1,(1-PSDLED)*(SCDD.K(DI)-DSTD.K(DI)),
                              0,FPCOMD.K(DI),PSDLED)
           REDUCTION OF LEARNING OVER A PERCEIVED
            PROGRESS IN DESIGN (DIMENSIONLESS)
C PSDLED=.7
           PROGRESS OF DESIGN BEFORE STARTING TO
            DECREASE THE LEARNING EFFECT
            (DIMENSIONLESS)
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A  WFNEED.K(DI)=(WCWFD.K(DI)*IWFDWR.K(DI))+
            (1-WCWFD.K( DI))*TDWF.K(DI)
         WORKFORCE NEEDED IN DESIGN (PERSON)
A WCWFD.K(DI)=TABHL(TWCWFD,FPCOMD.K(DI),0,1,.2)
         WILLINGNESS TO CHANGE WORKFORCE IN DESIGN
          (DIMENSIONLESS)
T TWCWFD=1,1,1,1,1,1
         TABLE FOR THE WILLINGNESS TO CHANGE
          WORKFORCE IN DESIGN (DIMENSIONLESS)
A DWFS.K(DI)=MIN(CELDWF.K(DI),WFNEED.K(DI))
         DESIGN WORKFORCE SOUGHT (PERSON)
A CELDWF.K(DI)=TABHL(TCDWF,FPCOMD.K(DI),0,1,.2)
         CEILING ON DESIGN WORKFORCE (PERSON)
T TCDWF=2000,2000,2000,2000,2000,2000
         TABLE FOR CEILING ON DESIGN WORKFORCE
          (PERSON)
A WFGAPD.K(DI)=DWFS.K(DI)-TDWF.K(DI)
         WORKFORCE GAP IN DESIGN(PERSON)
R HIRERD.KL(DI)=MAX(0,WFGAPD.K(DI)/HIRDYD(DI))
         HIRING RATE IN DESIGN (PERSON/WEEK)
P HIRDYD=3,3,3,3,3,
         HIRING DELAY IN DESIGN (WEEKS)
A TDWF.K(DI)=(WFEXPD.K(DI)+WFNEWD.K(DI))*
               CLIP(0,1,FPCOMD.K(DI),1)
         TOTAL DESIGN WORKFORCE IN EACH SPECIALTY
          (PERSON)
L WFNEWD.K(DI)=WFNEWD.J(DI)+DT*(HIRERD.JK(DI)-
            ASIMRD.JK(DI)-NEWTRD.J(DI))
N WFNEWD(DI)=0
         WORKFORCE NEW IN DESIGN (PERSON)
R ASIMRD.KL(DI)=(WFNEWD.K(DI)/ASIDYD(DI))*
                CLIP(0,1,FPCOMD.K(DI),1)
         ASSIMILATION RATE IN DESIGN (PERSON/WEEK)
P ASIDYD=6,6,6,6,6
         ASSIMILATION DELAY IN DESIGN (WEEK)
L CWFDD.K(DI)=CWFDD.J(DI)+DT*(TDWF.J(DI)*NBERDW)
N CWFDD(DI)=0
         CUMULATIVE WORKFORCE-DAYS IN DESIGN
          (PERSON-DAYS)
A NEWTRD.K(DI)=MIN(TRNFRD.K(DI),WFNEWD.K(DI)/DT)
         NEW TRANSFER RATE IN DESIGN (PERSON/WEEK)
A TRNFRD.K(DI)=MAX(0,-WFGAPD.K(DI)/TRNSDY(DI))
         TRANSFER RATE IN DESIGN (PERSON/WEEK)
P TRNSDY=2,2,2,2,2
         TRANSFER DELAY (WEEKS)
L WFEXPD.K(DI)=WFEXPD.J(DI)+DT*(ASIMRD.JK(DI)-
                EXPTRD.J(DI)-QUITRD.JK(DI))
N WFEXPD(ARC)=(.28*IW(ARC))/(GPRODD(ARC)*SCDND(ARC))
N WFEXPD(CIV)=0
N WFEXPD(MEC)=0
N WFEXPD(ELE)=0
N WFEXPD(INT)=0
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           WORKFORCE WITH EXPERIENCE IN DESIGN (PERSON)
R QUITRD.KL(DI)=(WFEXPD.K(DI)/AVEMTD(DI))*
                    CLIP(0,1,FPCOMD.K(DI),1)
           QUIT RATE IN DESIGN (PERSON/WEEK)
P AVEMTD=70,70,70,70,70
           AVERAGE EMPLOYMENT TIME (WEEK)
A EXPTRD.K(DI)=MIN(WFEXPD.K(DI)/DT,
                    TRNFRD.K(DI)-NEWTRD.K(DI))*
                        CLIP(0,1,FPCOMD.K(DI),1)
           EXPERIENCED WORKFORCE TRANSFERRED IN DESIGN
            (PERSON/WEEK)

A IWFDWR.K(DI)=(DEPREM.K(DI)/MAX(TREMD.K(DI),1))*
                 RTRAFD.K(DI)*
         CLIP(1,0,TIME.K,SCDND.K(DI)-DURDN(DI))
           INDICATED WORKFORCE IN DESIGN WITHOUT
            TAKING INTO ACCOUNT OF RELATIONS (PERSON)
A FIWFD.K(DI3-1)=CLIP(1,0,FPCOMD.K(DI3+2),PA DBCD)*
            CLIP(CLIP(1,0,FPCOMD.K(DI3),PMCCD),
                        1,FPCOMD.K(DI3-1),PCSMD)*
            CLIP(CLIP(1,0,FPCOMD.K(DI3+1),PECCD),
                        1,FPCOMD.K(DI3-1),PCSED)*
                 CLIP(0,1,FPCOMD.K(DI3-1),1)
           FACTOR FOR THE INDICATED CIVIL WORKFORCE IN
            DESIGN TAKING INTO ACCOUNT OF RELATIONS
            (DIMENSIONLESS)
C PADBCD=.05
           PROGRESS OF ARCHITECTURAL DESIGN BEFORE
            CIVIL DESIGN STARTING (DIMENSIONLESS)
C PMCCD=.03
           PROGRESS OF MECHANICAL TO CONTINUE THE CIVIL
            DESIGN (DIMENSIONLESS)
C PCSMD=.85
           PROGRESS OF CIVIL TO STUDY THE MECHANICAL
            DESIGN (DIMENSIONLESS)
C  PECCD=.2
           PROGRESS OF ELECTRICAL TO CONTINUE THE CIVIL
            DESIGN (DIMENSIONLESS)
C PCSED=.85
           PROGRESS OF CIVIL TO STUDY THE ELECTRICAL
            DESIGN (DIMENSIONLESS)
A FIWFD.K(DI3)=
      CLIP(1,0,FPCOMD.K(DI3+2),PADBMD)*
 CLIP(CLIP(1,0,FPCOMD.K(DI3+1)-FPCOMD.K(DI3),-DEMCMD),
            1,FPCOMD.K(DI3),PMSPE)*
 CLIP(CLIP(1,0,FPCOMD.K(DI3+3),FPCOMD.K(DI3)),-DIMCMD)
           ,1,FPCOMD.K(DI3),PMSID)*
      CLIP(0,1,FPCOMD.K(DI3),1)
           FACTOR FOR THE INDICATED MECHANICAL
            WORKFORCE IN DESIGN TAKING INTO ACCOUNT OF
            RELATIONS (DIMENSIONLESS)
C PADBMD=.05
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                PROGRESS OF ARCHITECTURAL DESIGN BEFORE
                 MECHANICAL DESIGN (DIMENSIONLESS)
C DEMCMD=.5
                DIFFERENCE BETWEEN ELECTRICAL & MECHANICAL
                 TO CONTINUE THE MECHANICAL DESIGN
                 (DIMENSIONLESS)
C PMSPE=.6
                PROGRESS OF MECHANICAL TO STUDY THE PROGRESS
                 WITH ELECTRICAL DESIGN (DIMENSIONLESS)
C PMSID=.85
                PROGRESS OF MECHANICAL TO STUDY THE INTERIOR
                 DESIGN (DIMENSIONLESS)
C DIMCMD=.5
                DIFFERENCE BETWEEN INTERIOR AND MECHANICAL
                 TO CONTINUE THE MECHANICAL DESIGN
                 (DIMENSIONLESS)
A FIWFD.K(DI3+1)=
             CLIP(1,0,FPCOMD.K(DI3+2),PACED)*
CLIP(MIN(CLIP(1,0,FPCOMD.K(DI3)-FPCOMD.K(DI3+1),-.3)
            ,CLIP(1,0,FPCOMD.K(DI3+2),FPCOMD.K(DI3+1),-.3))
                   ,1,FPCOMD.K(DI3+1),PESPAD)*
     CLIP(CLIP(1,0,FPCOMD.K(DI3+3)-FPCOMD.K(DI3+1),
                                               -DIECED),
                    1,FPCOMD.K(DI3+1),PESIED)*
             CLIP(0,1,FPCOMD.K(DI3+1),1)
               FACTOR FOR THE INDICATED ELECTRICAL
                WORKFORCE IN DESIGN TAKING INTO ACCOUNT
                RELATIONS (DIMENSIONLESS)
C PACED=.05
               PROGRESS OF ARCHITECTURAL TO CONTINUE THE
                ELECTRICAL DESIGN (DIMENSIONLESS)
C PESPAD=.6
               PROGRESS OF ELECTRICAL TO STUDY THE PROGRESS
                OF ARC AND MEC DESIGN (DIMENSIONLESS)
C DIECED=.85
               DIFFERENCE BETWEEN INTERIOR & ELECTRICAL TO
                CONTINUE THE ELECTRICAL  DESIGN
                (DIMENSIONLESS)
C PESIED=.85
               PROGRESS OF ELECTRICAL TO STUDY THE INTERIOR
                & ELECTRICAL DESIGN (DIMENSIONLESS)
A FIWFD.K(DI3+2)=CLIP(CLIP(1,0,FPCOMD.K(DI3-1)-
                               FPCOMD.K(DI3+2),-DACCAD)
                             ,1,FPCOMD.K(DI3+2),PASPCD)*
                  CLIP(CLIP(1,0,FPCOMD.K(DI3),FPASMD),
                              1,FPCOMD.K(DI3+2),PCCAD)*
                  CLIP(CLIP(1,0,FPCOMD.K(DI3+1),PECAD),
                              1,FPCOMD.K(DI3+2),FPASED)*
                       CLIP(0,1,FPCOMD.K(DI3+2),1)
               FACTOR FOR THE INDICATED ARCHITECTURAL
                WORKFORCE IN DESIGN TAKING INTO ACCOUNT OF
                RELATIONS (DIMENSIONLESS)
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C PASPCD=.4
          PROGRESS OF ARCHITECTURAL TO STUDY THE
           PROGRESS OF CIVIL DESIGN (DIMENSIONLESS)
C FPASMD=.4
          FURTHER PROGRESS OF ARCHITECTURAL TO STUDY
           THE MECHANICAL DESIGN (DIMENSIONLESS)
C PCCAD=.85
          PROGRESS OF CIVIL TO COMPLETE THE
           ARCHITECTURAL DESIGN (DIMENSIONLESS)
C PECAD=.4
          PROGRESS OF ELECTRICAL TO COMPLETE THE
           ARCHITECTURAL DESIGN (DIMENSIONLESS)
C FPASED=.85
          FURTHER PROGRESS OF ARCHITECTURAL TO STUDY
           THE ELECTRICAL DESIGN (DIMENSIONLESS)
C DACCAD=.4
          DIFFERENCE BETWEEN ARCHITECTURE AND CIVIL
           (DIMENSIONLESS)
A FIWFD.K(DI3+3)=CLIP(1,0,FPCOMD.K(DI3+2),PADBID)*
                CLIP(1,0,FPCOMD.K(DI3),PMDBID)*
                CLIP(1,0,FPCOMD.K(DI3+1),PEDBID)*
                CLIP(0,1,FPCOMD.K(DI3+3),1)
          FACTOR FOR THE INDICATED INTERIOR WORKFORCE
           IN DESIGN TAKING INTO ACCOUNT RELATIONS
           (DIMENSIONLESS)
C PADBID=.6
          PROGRESS OF ARCHITECTURAL DESIGN BEFORE
           INTERIOR DESIGN (DIMENSIONLESS)
C PMDBID=.3
          PROGRESS OF MECHANICAL DESIGN BEFORE
           INTERIOR DESIGN (DIMENSIONLESS)
C PEDBID=.3
          PROGRESS OF ELECTRICAL DESIGN BEFORE
           INTERIOR DESIGN (DIMENSIONLESS)
A TPDMD.K(DI)=(DEPREM.K(DI)*NBERDW)+CWFDD.K(DI)
          TOTAL PERCEIVED DESIGN MAN-DAYS
           (PERSON-DAYS)
A RFCOMD.K(DI)=DNNR.K(DI)/(IW(DI)+TWA.K(DI))
          REAL FRACTION COMPLETE IN DESIGN
           (DIMENSIONLESS)
L WRSPD.K(DI)=
         WRSPD.K(DI)=TABHL(TWRSPD,FPCOMD.K(DI),0,1,.2)
          WILLINGNESS TO RECOGNIZED PRESSURE DUE TO
           PROGRESS IN DESIGN (DIMENSIONLESS)
T TWRSPD=0,0,0,1,1,1
          TABLE FOR WILLINGNESS TO RECOGNIZE SCHEDULE
           PRESSURE IN DESIGN (WEEK)
A TDWFAS.K=SUM(TDWF.K)
          TOTAL DESIGN WORKFORCE FOR ALL SPECIALTIES
           (PERSON)
L UDR.K(DI)=UDR.J(DI)+DT*RDUDNR.JK(DI)
          UNDISCOVERED DRAWINGS TO REWORK (DRAWINGS)
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L DRDC.K(DI)=DRDC.J(DI)+DT*DTRDC.JK(DI)
            DRAWINGS TO REWORK DUE TO DESIGN CHANGE
             (DRAWINGS)
```

Construction Subsystem

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A QC.K(DI)=SMOOTH(TABHL(TQC,FPCOMC.K(DI),0,1,.2)*
      EQDRC.K(DI)*CWEQ.K(DI)*SCPEQC.K(DI)*EFDMQ.K(DI),
                                                QDEL(DI))
            QUALITY OF CONSTRUCTION (DIMENSIONLESS)
T TQC=.99,.97,.94,.93,.96,.92
            TABLE FOR QUALITY OF CONSTRUCTION
             (DIMENSIONLESS)
P QDEL=5,5,5,5,5
            QUALITY DELAY (WORKING WEEK)
A CWEQ.K(DI)=TABHL(TWEQ,CWFQF.K(DI),0,1,.2)
            EFFECT OF CONST WORKFORCE WITH EXPERIENCE
             ON QUALITY (DIMENSIONLESS)
A CWFQF.K(DI)=CWFEXP.K(DI)/MAX(TCWF.K(DI),1)
            CONST WORKFORCE QUALITY FACTOR
             (DIMENSIONLESS)
A SCPEQC.K(DI)=(TABHL(TSCPEQ,RCPPPC.K(DI),1,3,.25)*
              (WRSPC.K(DI))+(1-WRSPC.K(DI))
            SCHEDULE PRESSURE EFFECT ON QUALITY IN
             CONST (DIMENSIONLESS)
T TSCPEQ=1,1,1,.93,.87,.85,.85
            TABLE FOR SCHEDULE PRESSURE ON QUALITY
             (DIMENSIONLESS)
A EFDMQ.K(DI)=TABHL(TEFDMQ,RMSMN.K(DI),.7,1,.1)
            EFFECT OF DELIVERY OF MATERIAL ON QUALITY OF
             CONST (DIMENSIONLESS)
T TEFDMQ=.85,.92,.97,1
            TABLE FOR THE EFFECT OF DELIVERY OF MATL
             ON QUALITY OF CONST
A RRDCTD.K(DI)=DTRASC.K(DI)/(TWA.K(DI)+IW(DI))
            RATIO REVISED DRAWINGS DURING THE CONST. TO
             TOTAL DRAWINGS (DIMENSIONLESS)
L DTRASC.K(DI)=DTRASC.J(DI)+DT*RDRASC.J(DI)
N DTRASC(DI)=0
            DRAWINGS TO REWORK AFTER THE CONSTRUCTION
             START (DRAWING)
A RCPPPC.K(DI)=SWITCH(1,
            CAPRGC.K(DI)/MAX(FPCOMC.K(DI),.01),
                               FPCOMC.K(DI))
            RATIO OF CALIBRATED PROGRESS TO
             PERCEIVED PROGRESS IN CONST
             (DIMENSIONLESS)
A EQDRC.K(DI)=TABHL(TQMRDC,RRDCTD.K(DI),0,1,.2)
            EFFECT ON QUALITY OF DESIGN REVISED
             DURING THE CONST (DIMENSIONLESS)
T TQMRDC=1,.99,.98,.96,.96,.96
            TABLE FOR QUALITY MOTIVATION OF WORKERS DUE
```

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               TO REVISED DESIGN IN CONST (DIMENSIONLESS)
A CAPRGC.K(DI)=TABHL(TCAPRC,TPRGRC.K(DI),0,1,.1)
T TCAPRC=0,.05,.1,.2,.33,.44,.55,.66,.77,.9,1
              CALIBRATED PROGRESS IN CONST
               (DIMENSIONLESS)
T TCAPRC=0,.05,.1,.2,.33,.44,.55,.66,.77,.9,1
              TABLE FOR CALIBRATED PROGRESS IN CONST
               (DIMENSIONLESS)
A TPRGRC.K(DI)=
     SWITCH(1,CLIP(1,
              (TIME.K-DSTC.K(DI))/(SCDC.K(DI)-DSTC.K(DI)),
                   FPCOMC.K(DI),1),
                   FPCOMC.K(DI))
              TIME PROGRESS IN CONST (DIMENSIONLESS)
L DSTC.K(DI)=DSTC.J(DI)+DT*DSDC.J(DI)*(1/DT)
N DSTC(DI)=0
              DETERMINATION OF START TIMES IN CONST (WEEK)
A DSDC.K(DI)=MAX(0,TIME.K*3*DT)*
           CLIP(1,0,FLARIC.JK(DI)*DT,1)
              DETERMINATION OF START DATES IN CONST
               (WEEK)
R FLARIC.KL(DI)=SWITCH(0,1,FPCOMC.K(DI)*
                    CLIP(0,1,FLAGCS.K(DI),1)/DT
              "FLAG" RATE INDICATOR IN CONST TO DETERMINE
               START DATES IN CONST (1/WEEK)
L FLAGCS.K(DI)=FLAGCS.J(DI)+DT*FLARIC.JK(DI)
N FLAGCS(DI)=0
               "FLAG" IN CONST FOR START DATES (FLAG)
A CPCP.K(DI)=CNNR.K(DI)+UCNR.K(DI)
              CUMULATIVE PERCEIVED CONSTRUCTION PROGRESS
               (CONST JOB)
A FPCOMC.K(DI)=CPCP.K(DI)/TPCJ.K(DI)
              FRACTION PERCEIVED COMPLETED IN CONSTRUCTION
               (DIMENSIONLESS)
A RFCOMC.K(DI)=CNNR.K(DI)/MAX(TPCJ.K(DI),1)
              REAL FRACTION COMPLETED IN CONST
               (DIMENSIONLESS)
A CEPREM.K(DI)=(TPCJ.K(DI)-CPCP.K(DI))/
          SWITCH(GPRODC(DI),CPPROD.K(DI),FPCOMC.K(DI))
              CONST EFFORT PERCEIVED REMAINING
               (PERSON-WEEK)
C GPRODC=.2/.2/.2/.2/.2
              GROSS PRODUCTIVITY IN CONST (CONSTRUCTION
               JOBS/PERSON-WEEK)
A CPPROD.K(DI)=SMOOTH(IPRODC.K(DI),TPPROD(DI))
              CONST PERCEIVED PRODUCTIVITY (CONST
               JOB/PERSON-WEEK)
A IPRODC.K(DI)=WTRPC.K(DI)*CRPROD.K(DI)+
               (1-WTRPC.K(DI))*GPRODC(DI)
              INDICATED PRODUCTIVITY IN CONST (CONST
               JOB/PERSON-WEEK)
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A WTRPC.K(DI)=TABHL(TWTRP,FPCOMC.K(DI),0,1,.1)
           WILLINGNESS TO REAL PRODUCTIVITY IN
            CONST (DIMENSIONLESS)
A CRPROD.K(DI)=
   CLIP(CNNR.K(DI)/((CCWFD.K(DI)+1)/NBERDW),
      CNNRPD.K(DI)/((CWFEXP.K(DI)+CWFNEW.K(DI)+1)*DT),
                     FPCOMC.K(DI),.99)
           CONSTRUCTION REAL PRODUCTIVITY (CONST
            JOB/PERSON-WEEK)
L CNNRPD.K(DI)=CNNRPD.J(DI)+DT*(RCNNR.JK(DI)-
                               (CNNRPD.J(DI)/DT))
N CNNRPD(DI)=0
           PROGRESS NOT NEEDING REWORK TO FIND REAL
            PRODUCTIVITY PER DELTA TIME (CONST JOB)

A TPCJ.K(DI)=(IW(DI)+TWA.K(DI))*RCD(DI)
              +UCR.K(DI)+CTRRD.K(DI)
           TOTAL PERCEIVED CONSTRUCTION JOBS
            (CONSTRUCTION JOBS)
C RCD=6,6,6,6,6
           RATIO CONSTRUCTION TO DESIGN MAN-HOURS
            (DIMENSIONLESS)
A TPREQC.K(DI)=SWITCH(DURCN(DI),
            CEPREM.K(DI)*RTRAFC.K(DI)/MAX(CWFS.K(DI),
                       1),FPCOMC.K(DI))
           TIME PERCEIVED REQUIRED IN CONST (WEEK)
C DURCN=40,40,40,40,40
           DURATION OF SPECIALTIES IN CONST
            INITIALLY (WEEK)
A RTRAFC.K(DI)=TABHL(TRTRFC,FPCOMC.K(DI),0,1,.1)
           REQUIRED TRAPEZOIDAL FACTOR IN CONST
            (DIMENSIONLESS)
T TRTRFC=.15,.45,.71,.97,1.29,1.37,1.51,1.82,1.68,
            1.56,.01
           TABLE FOR REQUIRED TRAPEZOIDAL FACTOR IN
            CONST (DIMENSIONLESS)
A ICDC.K(DI)=SWITCH(CDCAD.K(DI),
                   CDCNAD.K(DI),WTDBCE(DI))
           INDICATED COMPLETION DATE IN CONSTRUCTION
            (WEEK)
B WTDBCE(DI)=1,1,1,1,1
           WILLINGNESS TO TAKE INTO ACCOUNT OF DESIGN
            COMPLETION DATE FOR CONST END
            (DIMENSIONLESS)
A CDCAD.K(DI3-1)=SWITCH(DARSCD.K(DI3-1),
              TIME.K+TPREQC.K(DI3-1),
                     FPCOMC.K(DI3-1))
           COMPLETION DATE OF CIV CONST TAKING INTO
            ACCOUNT THE DESIGN COMPLETION DATE (WEEK)
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A CDCNAD.K(DI3-1)=SWITCH(
                  MAX(SCDD.K(DI3-1),SCDCN.K(DI3-1)),
                            TIME.K+TPREQC.K(DI3-1),
                                 FPCOMC.K(DI3-1))
          COMPLETION DATE OF CIV CONST NOT TAKING
           INTO ACCOUNT OF DESIGN COMPLETION DATE
           (WEEK)
A CDCAD.K(DI3)=SWITCH(DARSCD.K(DI3),
              TIME.K+LTBSC.K(DI3),FPCOMC.K(DI3))
          COMPLETION DATE OF MEC CONST TAKING INTO
           ACCOUNT  OF DESIGN COMPLETION DATE (WEEK)
A CDCNAD.K(DI3)=SWITCH(MAX(SCDD.K(DI3),SCDCN.K(DI3)),
                 TIME.K+LTBSC.K(DI3),FPCOMC.K(DI3))
          COMPLETION DATE OF MEC CONST NOT TAKING INTO
           ACCOUNT OF DESIGN COMPLETION DATE (WEEK)
A CDCAD.K(DI3+1)=SWITCH(DARSCD.K(DI3+1),
          TIME.K+LTBSC.K(DI3+1),FPCOMC.K(DI3+1))
          COMPLETION DATE OF ELEC CONST TAKING INTO
           ACCOUNT OF DESIGN COMPLETION DATE (WEEK)
A CDCNAD.K(DI3+1)=
           SWITCH(MAX(SCDD.K(DI3+1),SCDCN.K(DI3+1)),
             TIME.K+LTBSC.K(DI3+1),FPCOMC.K(DI3+1))
          COMPLETION DATE OF ELEC CONST NOT TAKING
           INTO ACCOUNT OF DESIGN COMPLETION DATE
           (WEEK)
A CDCAD.K(DI3+2)=SWITCH(DARSCD.K(DI3+2),
               TIME.K+LTBSC.K(DI3+2),
                    FPCOMC.K(DI3+2))
          COMPLETION DATE OF ELEC CONST TAKING INTO
           ACCOUNT OF DESIGN COMPLETION DATE (WEEK)
A CDCNAD.K(DI3+2)=
           SWITCH(MAX(SCDD.K(DI3+2)),SCDCN.K(DI3+2)),
                    TIME.K+LTBSC.K(DI3+2)),
                         FPCOMC.K(DI3+2))
          COMPLETION DATE OF ELEC CONST NOT TAKING
           INTO ACCOUNT OF DESIGN COMPL DATE (WEEK)
A CDCAD.K(DI3+3)=
      SWITCH(DARSCD.K(DI3+3),
             TIME.K+LTBSC.K(DI3+3),FPCOMC.K(DI3+3))
          COMPLETION DATE OF INT CONST TAKING INTO
           ACCOUNT OF DESIGN COMPLETION DATE (WEEK)
A CDCNAD.K(DI3+3)=
           SWITCH(MAX(SCDD.K(DI3+3)),SCDCN.K(DI3+3)),
             TIME.K+LTBSC.K(DI3+3),FPCOMC.K(DI3+3))
          COMPLETION DATE OF INT CONST NOT TAKING
           INTO ACCOUNT OF DESIGN COMPLETION DATE
           (WEEK)
L SCDC.K(DI)=SCDC.J(DI)+DT*NACS.JK(DI)
N SCDC(DI)=SCDCN(DI)
          SCHEDULE COMPLETION DATE IN CONSTRUCTION
           (WEEK)
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A SCDCN.K(DI3)=CONSST+(DURCN(DI3-1)*PPCBMW)+DURCN(DI3)
           SCHEDULE COMPLETION DATE IN MECHANICAL
            CONSTRUCTION INITIALLLY (WEEK)
C CONSST=50
           CONST START TIME (WEEK)
C PPCBMW=.3
           PERCENT PROGRESS OF CIVIL BEFORE MEC WORK
            START (DIMENSIONLESS)
A SCDCN.K(DI3+1)=CONSST+(DURCN(DI3-1)*PPCBEW)+
                        DURCN(DI3+1)
           SCHEDULE COMPLETION DATE IN ELECTRICAL
            CONSTRUCTION INITIALLLY (WEEK)
C PPCBEW=.4
           PERCENT PROGRESS OF CIVIL BEFORE
            ELECTRICAL WORK START (DIMENSIONLESS)
A SCDCN.K(DI3-1)=CONSST+DURCN(DI3-1)
           SCHEDULE COMPLETION DATE IN CIVIL
            CONSTRUCTION INITIALLLY (WEEK)
A SCDCN.K(DI3+2)=CONSST+(DURCN(DI3-1)*PPCBAW)+
                        DURCN(DI3+2)
           SCHEDULE COMPLETION DATE IN ARCHITECTURAL
            CONSTRUCTION INITIALLLY (WEEK)
C PPCBAW=.2
           PERCENT PROGRESS OF CIVIL BEFORE
            ARCHITECTURAL WORK START (DIMENSIONLESS)
A SCDCN.K(DI3+3)=CONSST+(DURCN(DI3+1)*PPEBIW)+
                        DURCN(DI3+3)
           SCHEDULE COMPLETION DATE IN INTERIOR
            CONSTRUCTION INITIALLLY (WEEK)
C PPEBIW=.5
           PERCENT PROGRESS OF ELECTRICAL BEFORE
            INTERIOR WORK START (DIMENSIONLESS)
R NACS.KL(DI)=(ICDC.K(DI)-SCDC.K(DI))/CSAT.K(DI)*
              CLIP(0,1,RFCOMC.K(DI))
           NET ADDITION TO CONST SCHEDULE (WEEK/WEEK)
A CSAT.K(DI)=TABHL(TSATC,FPCOMC.K(DI),0,1,.2)
            CONST SCHEDULE ADJUSTEMENT TIME (WEEK)
T TSATC=20,20,10,6,4,3
            TABLE FOR SCHEDULE ADJUSTMENT TIME IN CONST
             (WEEK)
A TREMC.K(DI)=SWITCH(SCDC.K(DI)-TIME.K,DURCN(DI),
             FPCOMC.K(DI))*CLIP(0,1,RFCOMC.K(DI),1)
            TIME REMAINING IN CONSTRUCTION (WEEK)

           RATE OF UNDISCOVERED CONST JOBS NEEDING
            REWORK (CONST JOBS/WEEK)
L UCNR.K(DI)=UCNR.J(DI)+DT*(RUCNR.JK(DI)-RDUCNR.JK(DI))
N UCNR(DI)=0
           UNDISCOVERED CONST JOBS NEEDING REWORK
                  (CONSTRUCTION JOBS)
R RDUCNR.KL(DI)=UCNR.K(DI)/TDCRW.K(DI)
           RATE OF DETECTION OF UNDISCOVERED CONST
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            JOBS NEEDING REWORK (CONSTRUCTION
            JOBS/WEEK)
A TDCRW.K(DI)=TABHL(TTDRW,FPCOMC.K(DI),0,1,.1)
           TIME TO DETECT CONST REWORK (WEEK)
L CNNR.K(DI)=CNNR.J(DI)+DT*(RCNNR.JK(DI)-RCTRRD.JK(DI))
N CNNR(DI)=0
           CONST NOT NEEDING REWORKED (CONSTRUCTION
            JOBS)
R RCNNR.KL(DI)=APPRGC.K(DI)*QC.K(DI)
           RATE OF CONSTRUCTION NOT NEEDING REWORK
            (CONSTRUCTION JOBS/WEEK)
R RCTRRD.KL(DI)=
   CLIP(RDRASC.K(DI)*RCD(DI)/TDCR(DI),0,
          CNNR.K(DI)-(DTRASC.K(DI)*RCD(DI)/TDCR(DI)),0)
           RATE OF CONST TO REWORK DUE TO REVISED
            DESIGN (CONST JOBS/WEEK)
P TDCR=4,4,4,4,4
           TIME TO DETECT CONST TO REWORK (WEEKS)
A RDRASC.K(DI)=(RDUDNR.JK(DI)+DTRDC.JK(DI)+
                 DTRWA.JK(DI))*SWITCH(0,1,FPCOMC.K(DI))
           RATE OF DRAWINGS TO REWORK AFTER THE START
            OF THE CONST (DRAWING/WEEK)
A APPRGC.K(DI)=TCWF.K(DI)*APRODC.K(DI)
           APPARENT PROGRESS (CONST JOB/WEEK)
A APRODC.K(DI)=GPRODC(DI)*SCPEPC.K(DI)*EFDMP.K(DI)*
                          LEPROC.K(DI)*EFAWLC.K(DI)*
                           EFJSC.K(DI)*EFOVTC.K(DI)*
                                        FICWF.K(DI)
           APPARENT PRODUCTIVITY IN CONST (CONST
            JOBS/PERSON-WEEK)
A SCPEPC.K(DI)=(TABHL(TSPEP,RCPPPC.K(DI),.75,2,.25)*
             WRSPC.K(DI))+(1-WRSPC.K(DI))
           SCHEDULE PRESSURE EFFECT ON PRODUCTIVITY
            IN CONST (DIMENSIONLESS)
A LEPROC.K(DI)=TABHL(TLEPC,FPCOMC.K(DI),0,1,.1)
                           -RLOPPC.K(DI)-EVLC.K(DI)
           LEARNING EFFECT IN CONST (DIMENSIONLESS)
T TLEPC=.9,.95,1,1.04,1.07,1.09,1.1,1.105,1.11,
        1.11,1.11
           TABLE FOR THE LEARNING EFFECT ON
            PRODUCTIVITY IN CONSTRUCTION
            (DIMENSIONLESS)
A EVLC.K(DI)=PULSE(V1(DI)/DT,DT/DT,V2.K(DI),V3(DI))
           EFFECT OF VACATIONS ON LEARNING IN CONST
            (DIMENSIONLESS)
P V1=.05,.05,.05,.05,.05
           FACTOR FOR THE EFFECT OF VACATIONS ON
            LEARNING (WEEK)
P V3=24,24,24,24,24
           INTERVAL TIME FOR THE EFFECT OF
            VACATIONS ON LEARNING (DIMENSIONLESS)
A V2.K(DI)=CONSST+24
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           FIRST TIME FOR THE EFFECT OF VACATIONS ON
            LEARNING EFFECT (WEEK)
A RLOPPC.K(DI)=CLIP(SMOOTH(.1,(1-PSDLEC)*DSC.K(DI)),
                  0,FPCOMC.K(DI),PSDLEC)
            REDUCTION OF LEARNING OVER A PERCEIVED
             PROGRESS IN CONST (DIMENSIONLESS)
T PSDLEC=.7
           PROGRESS TO START TO DECREASE THE LEARNING
            EFFECT IN CONST (DIMENSIONLESS)
A DSC.K(DI)=SCDC.K(DI)-DSTC.K(DI))
           DURATION OF SPECIALTIES IN CONST (WEEK)
A EFAWLC.K(DI)=TABHL(TEFAWL,RATCWF.K(DI),80,160,20)
           EFFECT OF AREA WORKLOAD IN CONST
            (DIMENSIONLESS)
T TEFAWL=.85,.9,.95,.98,1
           TABLE FOR THE EFFECT OF AREA WORKLOAD IN
            CONST (DIMENSIONLESS)
A RATCWF.K(DI)=
 CLIP(200,CLIP(FLAREA*NBRFLR.K(DI)/6,
             2*FLAREA,FPCOMC.K(DI),.25)/(TCWF.K(DI)+1),
                    1-FPCOMC.K(DI),1)
           RATIO OF AREA TO TOTAL CONST WORKFORCE
            (SQUARE FOOT/PERSON)
C FLAREA=27000
           FLOOR AREA (SQUARE FEET)
A NBRFLR.K(DI)=(SCLPRD(IW,CIV,INT,RCD,CIV)+
             SCLPRD(TWA.K,CIV,INT,RCD,CIV))*
        NHWC.K(DI)*MHCOSC(DI)/(RMPTCC(DI).208*FLAREA
                                   *CCOSSF(DI))
           NUMBER OF FLOORS (FLOOR)
C MHCOSC=20,20,20,20,20
           MAN-HOUR COST IN CONSTRUCTION (DOLLAR/HOUR)
C RMPTCC=.33,.33,.33,.33,.33
           RATIO MANPOWER COST TO TOTAL CONSTRUCTION
            COST (DIMENSIONLESS)
C CCOSSF=85,85,85,85,85
           CONST COST PER SQUARE FOOT
            (DOLLARS/SQUARE FOOT)
C NBRHDC=8,8,8,8,8
           NUMBER OF HOURS PER DAY IN CONST (WORKING
            HOURS/DAY)
A NHWC.K(DI)=NBRHDC(DI)*NBERDW
           NUMBER OF HOURS PER WEEK IN CONST (HOUR)
A EFOVTC.K(DI)=TABLE(TEFOVT,RONHWC.K(DI),0,.8,.2)*
              ((NHWC.K(DI)+OVRTHC.K(DI))/NHWC.K(DI))
            EFFECT OF OVERTIME IN CONST (DIMENSIONLESS)
T TEFOVT=1,.9,.83,.75,.68
           TABLE FOR THE EFFECT OF OVERTIME IN
            CONST (DIMENSIONLESS)
A OVRTHC.K(DI)=(TABHL(TOVTC,RCPPPC.K(DI),1,2,.25)*
              WOVSPC(DI))+(FOVTAC.K(DI)*WOVRTA(DI))
            OVERTIME HOURS IN CONST (HOUR)
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T TOVTC=0,0,2,5,10
            TABLE FOR OVERTIME IN CONSTRUCTION (HOUR)
B WOVSPC=0,0,0,0,0
           WILLINGNESS FOR OVERTIME DUE TO SCHEDULE
            PRESSURE IN CONST. (DIMENSIONLESS)
B WOVRTA=0,0,0,0,0
           WILLINGNESS TO WORK ON OVERTIME DUE TO
            ACCELERATION IN CONST (DIMENSIONLESS)
A FOVTAC.K(DI3-1)=MIN(1,SWITCH(1,0,FICWFO.K(DI3)+
                       SWITCH(1,0,FICWFO.K(DI3+2))
                                          *NHOTCA)
           FACTOR FOR OVERTIME HOUR IN CONST DUE TO
            ACCELERATION (DIMENSIONLESS)
C NHOTCA=5
           NUMBER OF HOURS ON OVERTIME DUE TO
            ACCELERATION IN CONST (HOUR)
A FOVTAC.K(DI3)=SWITCH(1,0,FICWFO.K(DI3+1))*NHOTCA
           FACTOR FOR OVERTIME HOURS IN MECHANICAL
            CONST DUE TO ACCELERATION (DIMENSIONLESS)
A FOVTAC.K(DI3+1)=SWITCH(1,0,FICWFO.K(DI3+3))*NHOTCA
           FACTOR FOR OVERTIME HOURS IN ELECTRICAL
            CONST DUE TO ACCELERATION (DIMENSIONLESS)
A FOVTAC.K(DI3+2)=SWITCH(1,0,FICWFO.K(DI3+3))*NHOTCA
           FACTOR FOR OVERTIME HOURS IN ARCHITECTURAL
            CONST DUE TO ACCELERATION (DIMENSIONLESS)
A FOVTAC.K(DI3+3)=0
           FACTOR FOR OVERTIME HOURS IN INTERIOR
            CONST DUE TO ACCELERATION (DIMENSIONLESS)
A RONHWC.K(DI)=OVRTHC.K(DI)/NHWC.K(DI)
           RATIO OVERTIME TO NORMAL NUMBER OF HOURS
            PER WEEK IN CONST (DIMENSIONLESS)
A EFJSC.K(DI)=TABHL(TEFJSC,
                 TPCMD.K(DI)*NHWC.K(DI)/NBERDW,
                             0,6000000,1000000)
           EFFECT OF JOB SIZE IN CONST (DIMENSIONLESS)
T TEFJSC=1.06,1,.98,.97,.96,.95,.92
           TABLE FOR THE EFFECT OF JOB SIZE IN CONST
            (DIMENSIONLESS)

A CWFND.K(DI)=(WCCWF.K(DI)*ICWFTR.K(DI))+
             ((1-WCCWF.K(DI))*TCWF.K(DI))
           CONST WORKFORCE NEEDED (PERSON)
A WCCWF.K(DI)=TABHL(TWCCWF,FPCOMC.K(DI),0,1,.2)
           WILLINGNESS TO CHANGE CONST WORKFORCE
            (DIMENSIONLESS)
T TWCCWF=1,1,1,1,1,1
           TABLE FOR THE WILLINGNESS TO CHANGE
            CONST WORKFORCE (DIMENSIONLESS)
A CWFS.K(DI)=MIN(CLTCWF.K(DI),CWFND.K(DI))
           CONST WORKFORCE SOUGTH (PERSON)
A CLTCWF.K(DI)=TABHL(TCTCWF,FPCOMC.K(DI),0,1,.2)
           CEILING ON TOTAL CONST WORKFORCE (PERSON)
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T TCTCWF=6000,6000,6000,6000,6000,6000
          TABLE FOR CEILING ON TOTAL CONST
           WORKFORCE (PERSON)
A CWFGAP.K(DI)=CWFS.K(DI)-TCWF.K(DI)
          CONST WORKFORCE GAP (PERSON)
R CHIRER.KL(DI)=MAX(0,CWFGAP.K(DI)/CHIRDY(DI))
          CONST HIRING RATE (PERSON/WEEK)
C CHIRDY=2,2,2,2,2
          CONSTRUCTION HIRING DELAY (WEEK)
A TCWF.K(DI)=(CWFEXP.K(DI)+CWFNEW.K(DI))*
                 CLIP(0,1,RFCOMC.K(DI),1)
          TOTAL CONSTRUCTION WORKFORCE IN EACH
           SPECIALTY (PERSON)
L CWFNEW.K(DI)=CWFNEW.J(DI)+DT*(CHIRER.JK(DI)-
              ASIMRC.JK(DI)-NEWCTR.J(DI))
N CWFNEW(DI)=0
          CONSTRUCTION WORKFORCE THAT ARE NEW
           (PERSON)
B ASIMRC.KL(DI)=CWFNEW.K(DI)/ASIDYC(DI)
P ASIDYC=4,4,4,4,4
          ASSIMILATION RATE OF NEW PERSONS IN CONST
           (PERSON/WEEK)
L CCWFD.K(DI)=CCWFD.J(DI)+DT*(TCWF.J(DI)*NBERDW*
              ((NHWC.J(DI)+OVRTHC.J(DI))/NHWC.J(DI)))
N CCWFD(DI)=0
          CUMULATIVE CONST WORKFORCE-DAYS (PERSON-DAY)
A NEWCTR.K(DI)=MIN(TRNFRC.K(DI),CWFNEW.K(DI)/DT)
          NEW CONST TRANSFER RATE (PERSON/WEEK)
A TRNFRC.K(DI)=MAX(0,-CWFGAP.K(DI)/TRNSDY(DI))
          TRANSFER RATE OF PERSON IN CONST
           (PERSON/WEEK)
L CWFEXP.K(DI)=CWFEXP.J(DI)+DT*(ASIMRC.JK(DI)-
              EXPTRC.J(DI)-QUITRC.JK(DI))
N CWFEXP(DI)=0
          CONST WORKFORCE WITH EXPERIENCE (PERSON)
R QUITRC.KL(DI)=CWFEXP.K(DI)/AVEPTC(DI)
          QUIT RATE IN CONST (PERSON/WEEK)
P AVEPTC=60,60,60,60,60
          AVERAGE EMPLOYMENT TIME IN CONST (WEEK)
A EXPTRC.K(DI)=MIN(CWFEXP.K(DI)/DT,
                 TRNFRC.K(DI)-NEWCTR.K(DI))
          EXPERIENCED TRANSFERRED PERSONS IN CONST
           (PERSON/WEEK)
A ICWFWR.K(DI)=(CEPREM.K(DI)/(TREMC.K(DI)+1))*
              RTRAFC.K(DI)
             *CLIP(1,0,TIME.K,SCDCN.K(DI)-DURCN(DI))
          INDICATED CONST WORKFORCE WITHOUT TAKING
           INTO ACCOUNT OF RELATIONS (PERSON)
A WRSPC.K(DI)=TABHL(TWRSPC,FPCOMC,K(DI),0,1,.2)
          WILLINGNESS TO RECOGNIZE PRESSURE DUE TO
           PROGRESS IN CONST (DIMENSIONLESS)
T TWRSPC=0,0,0,1,1,1
```

```
           TABLE FOR THE WILLINGNESS TO RECOGNIZE
            PRESSURE DUE TO PROGRESS IN CONST
            (DIMENSIONLESS)
A ICWFTR.K(DI)=ICWFWR.K(DI)*FICWF.K(DI)
           INDICATED CONST WORKFORCE TAKING INTO
            ACCOUNT OF THE RELATIONS (PERSON)
A FICWF.K(DI3-1)=CLIP(1,0,TIME.K,CONSST)
           FACTOR FOR THE INDICATED CIVIL WORKFORCE
            TAKING INTO ACCOUNT OF RELATIONS
            (DIMENSIONLESS)
A FICWF.K(DI3)=CLIP(1,0,
                    FPCOMC.K(DI3-1)*NBRFLR.K(DI3),
      MIN(4,NBRFLR.K(DI3)))*CLIP(1,0,FPCOMC.K(DI3-1),
                                    FPCOMC.K(DI3))
           FACTOR FOR THE INDICATED MECHANICAL
            WORKFORCE TAKING INTO ACCOUNT OF RELATIONS
            (DIMENSIONLESS)
A FICWF.K(DI3+1)=
           CLIP(1,0,FPCOMC.K(DI3)-FPCOMC.K(DI3+1),-.10)
         *CLIP(1,0,FPCOMC.K(DI3-1)-FPCOMC.K(DI3+1),0)
           FACTOR FOR THE INDICATED ELECTRICAL
            WORKFORCE TAKING INTO ACCOUNT OF RELATIONS
            (DIMENSIONLESS)
A FICWF.K(DI3+2)=
          CLIP(1,0,FPCOMC.K(DI3-1)*NBRFLR.K(DI3+2),
                              MIN(4,NBRFLR.K(DI3)))*
          CLIP(1,0,FPCOMC.K(DI3-1)-FPCOMC.K(DI3+2),-.1)
           FACTOR FOR THE INDICATED ARCHITECTURAL
            WORKFORCE TAKING INTO ACCOUNT OF RELATIONS
            (DIMENSIONLESS)
A FICWF.K(DI3+3)=
           CLIP(1,0,FPCOMC.K(DI3)*NBRFLR.K(DI3+3),
                              MIN(2,NBRFLR.K(DI3)))*
         CLIP(1,0,FPCOMC.K(DI3+1)*NBRFLR.K(DI3+3),
                              MIN(2,NBRFLR.K(DI3)))*
         CLIP(1,0,FPCOMC.K(DI3+2)*NBRFLR.K(DI3+3),
                              MIN(2,NBRFLR.K(DI3)))*
           CLIP(1,0,FPCOMC.K(DI3)-FPCOMC.K(DI3+3),-.1)*
         CLIP(1,0,FPCOMC.K(DI3+1)-FPCOMC.K(DI3+3),-.1)*
         CLIP(1,0,FPCOMC.K(DI3+2)-FPCOMC.K(DI3+3),-.1)
           FACTOR FOR THE INDICATED INTERIOR WORKFORCE
            TAKING INTO ACCOUNT OF RELATIONS
            (DIMENSIONLESS)
A TPCMD.K(DI)=(CEPREM.K(DI)*NBERDW)+CCWFD.K(DI)
           TOTAL PERCEIVED CONST MAN-DAYS(PERSON-DAYS)
A DARSCD.K(DI)=SCDD(DI)-SCDND.K(DI)+SCDCN.K(DI)
           DURATION ADDS DUE TO THE REVISED SCHEDULE
            COMPLETION DATE IN DESIGN (WEEK)
A LTBSC.K(DI3-1)=0
           LATEST TIME FOR CIVIL WORK BETWEEN
            SPECIALTIES IN CONST (WEEK)
```

```
A LTBSC.K(DI3)=MAX(MAX(MAX(MAX(TPREQC.K(DI3-1),
                              TPREQC.K(DI3)),
                              TPREQC.K(DI3+1)),
                              TPREQC.K(DI3+2)),
                              TPREQC.K(DI3+3)*.9)
           LATEST TIME FOR MECHANICAL WORK BETWEEN
            SPECIALTIES IN CONST (WEEK)
A LTBSC.K(DI3+1)=LTBSC.K(DI3)
           LATEST TIME FOR ELECTRICAL WORK BETWEEN
            SPECIALTIES IN CONST (WEEK)
A LTBSC.K(DI3+2)=MAX(TPREQC.K(DI3-1),TPREQC.K(DI3+2))
           LATEST TIME FOR ARCHITECTURAL WORK BETWEEN
            SPECIALTIES IN CONST (WEEK)
A LTBSC.K(DI3+3)=MAX(MAX(MAX(TPREQC.K(DI3-1) ,
                          TPREQC.K(DI3)*.9),
                          TPREQC.K(DI3+1)),
                          TPREQC.K(DI3+3)*.9)
           LATEST TIME FOR INTERIOR WORK BETWEEN
            SPECIALTIES IN CONST (WEEK)
A FICWFO.K(DI)=SWITCH(1,CLIP(1,ICWFTR.K(DI),
              FPCOMC.K(DI),1),FPCOMC.K(DI))
           FACTOR FOR THE INDICATED CONST WORKFORCE
            TAKING INTO ACCOUNT OF RELATIONS (PERSON)
L UCR.K(DI)=UCR.J(DI)+DT*RDUCNR.JK(DI)
           UNDISCOVERED CONSTRUCTION TO REWORK (CONST
            JOBS)
L CTRRD.K(DI)=CTRRD.K(DI)+DT*RCTRRD.JK(DI)
           CONST TO REWORK DUE TO REVISED DERAWINGS
            (CONST-JOBS)
```

Procurement Subsysytem

```
A POMTL.K(DI)=TABHL(TPOMTL,FPCOMD.K(DI),0,1,.2)
           POTENTIAL ORDERS OF MATERIAL IN RELATION
            WITH DESIGN PROGRESS (PIECE)
T TPOMTL=0,0,.10,.25,.5,1
           TABLE FOR THE POTENTIAL ORDERS OF
            MATERIAL IN RELATION WITH DESIGN PROGRESS
            (PIECE)
L REQMTL.K(DI)=
          REQMTL.J(DI)+DT*(REQRML.JK(DI)-ODRMTL.JK(DI))
N REQMTL(DI)=0
           REQUISITIONS OF MATERIAL (PIECE)
R REQRML.KL(DI)=MIN(MAXRQM(DI),
    POMTL.K(DI)-REQMTL.K(DI)-MTLODR.K(DI)-MTLOST.K(DI))
                                           /REQDY(DI))
                              *CLIP(1,0,TIME.K,PROCST(DI))
           REQUISITIONS RATE OF MATERIAL
            (PIECE/WEEK)
C MAXRQM=.05,.05,.05,.05,.05
           MAXIMUM REQUISITIONS RATE OF MATERIAL
```

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               MAXIMUM REQUISITIONS RATE OF MATERIAL
                (PIECE/WEEK)
P REQDY=6,6,6,6,6
               REQUISITION DELAY (WEEK)
C PROCST=0,0,0,0,0
               PROCUREMENT START TIME (WEEK)
L MTLODR.K(DI)=
            MTLODR.J(DI)+DT*(ODRMTL.JK(DI)-DELRML.JK(DI))
N MTLODR(DI)=0
               MATERIAL ORDERS (DIMENSIONLESS)
R ODRMTL.KL(DI)=REQMTL.K(DI)/ORDY(DI)
               ORDERS RATE OF MATERIAL (%/WEEK)
P ORDY=4,4,4,4,4
               ORDERS DELAY (WEEK)
L MTLOST.K(DI)=MTLOST.J(DI)+DT*DELRML.JK(DI)
N MTLOST(DI)=0
               MATERIAL ON SITE (PIECE)
R DELRML.KL(DI)=MTLODR.K(DI)/DELDY.K(DI)
               DELIVERY RATE OF MATL (PIECE/WEEK)
A DELDY.K(DI)=TABHL(TDELDY,QDSD.K(DI),0,1,.2)
               DELIVERY DELAY (WEEK)
T TDELDY=20,20,20,16,14,8
               TABLE FOR DELIVERY DELAY (WEEK)
A QDSD.K(DI)=TABHL(TQDSD,AVQD.K(DI),.5,1,.1)
               QUALITY OF DESIGN OF SHOP DRAWINGS
                (DIMENSIONLESS)
T TQDSD=.5,.6,.7,.8,.9,1
               TABLE FOR THE QUALITY OF DESIGN OF SHOP
                DRAWINGS (DIMENSIONLESS)
A RMSMN.K(DI)=MTLOST.K(DI)/MAX(MTLND.K(DI),.001)
               RATIO OF MATL ON SITE TO MATL NEEDED
                (DIMENSIONLESS)
A EFDMP.K(DI)=TABHL(TEFDMP,RMSMN.K(DI),0,1,.2)
               EFFECT OF DELIVERY OF MATERIAL ON PROD
                (APPARENT) (DIMENSIONLESS)
T TEFDMP=0,.58,.70,.83,.93,1
               TABLE FOR THE EFFECT OF DELIVERY OF MATL ON
                PRODUCTIVITY (DIMENSIONLESS)
A MTLND.K(DI)=MIN(1,FPCOMC.K(DI)*DELYF(DI))
               MATERIAL NEEDED (IN THEORY)
                (DIMENSIONLESS)
C DELYF=1.1,1.1,1.1,1.1,1.1
               DELIVERY FACTOR (DIMENSIONLESS)
A APDWF.K(DI)=TDWF.K(DI)*NBERDW*NBRHDD(DI)*
                 DCOSTH(DI)*DT*
          ((1+(NESCFD.K(DI)/(48/DT)))**(TIME.K/DT))
               ACTUAL PAYMENT FOR DESIGN WORKFORCE
                (DOLLARS)
```

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A APCWFP.K(DI)=TCWF.K(DI)*NBERDW*
                          (NBRHDC(DI)+(OVRTHC.K(DI)*2))*
                          MHCOSC(DI)*PROCF(DI)*DT*
          ((1+(NESCFC.K(DI)/(48/DT)))**(TIME.K/DT))
           ACTUAL PAYMENT FOR CONSTRUCTION WORKFORCE
            AND PROCUREMENT (DOLLARS)
C PROCF=3.03,3.03,3.03,3.03,3.03
           PROCUREMENT COST FACTOR (DIMENSIONLESS)
A TAPAY.K=SUM(APDWF.K)+SUM(APCWFP.K)
           TOTAL ACTUAL PAYMENT (DOLLAR)
A FPAY.K=CAPAY.K*NINTRF.K/(48/DT)
           FINANCIAL PAYMENT (DOLLAR)
A NINTRF.K=(((1+EFINT)**(DT/48))-1)*(48/DT)
           NOMINAL INTEREST FACTOR (DIMENSIONLESS)
C EFINT=0.1
           EFFECTIVE INTEREST (DIMENSIONLESS)
A NESCFD.K(DI)=(((1+EFESCD(DI))**(DT/48))-1)*(48/DT)
           NOMINAL ESCALATION FACTOR FOR DESIGN
            (DIMENSIONLESS)
C EFESCD=.05,.05,.05,.05,.05
           EFFECTIVE ESCALATION COST (DIMENSIONLESS)
A NESCFC.K(DI)=(((1+EFESCC(DI))**(DT/48))-1)*(48/DT)
           NOMINAL ESCALATION FACTOR FOR
            CONSTRUCTION (DIMENSIONLESS)
C EFESCC=.05,.05,.05,.05,.05
           EFFECTIVE ESCALATION COST (DIMENSIONLESS)
L CAPAY.K=CAPAY.J+DT*(TAPAY.J+FPAY.J)*(1/DT)
N CAPAY=0
           CUMULATIVE ACTUAL PAYMENT (DOLLAR)
L PW.K=PW.J+DT*(((TAPAY.J+FPAY.J)*(1/DT))/
           (((1+(NINTRF.J/(48/DT)))**(TIME.J/DT))))
N PW=0
           PRESENT WORTH OF PAYMENT (DOLLAR)
A TDESC.K=SUM(TCOSTD.K)
           TOTAL DESIGN COST (DOLLAR)
A TCOSTD.K(DI)=
           TPDMD.K(DI)*NBRHDD(DI)*DCOSTH(DI)/RDTTPC(DI)
           TOTAL COST TAKING INTO ACCOUNT OF DESIGN
            COST (DOLLAR)
C DCOSTH=55,55,55,55,55
           DESIGN COST PER HOUR (DOLLARS/HOUR)
C RDTTPC=.16,.16,.16,.16,.16
           RATIO OF DESIGN COST TO TOTAL PROJECT
            COST (DIMENSIONLESS)
A CCCOS.K(DI)=CCWFD.K(DI)*NBRHDC(DI)*MHCOSC(DI)
           CUMULATIVE MANPOWER CONST COST (DOLLAR)
A TCONSC.K=SUM(CCCOS.K)
           TOTAL MANPOWER CONSTRUCTION COST (DOLLAR)
A TCOSTC.K(DI)=
          TPCMD.K(DI)*NBRHDC(DI)*MHCOSC(DI)/RMPTCC(DI)
           TOTAL COST TAKING INTO ACCOUNT THE CONST
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        COST (DOLLAR)
A TPCOST.K=(SUM(TCOSTD.K)+SUM(TCOSTC.K))/2
        TOTAL AVERAGE PROJECT COST (CONSTANT DOLLAR)
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APPENDIX 4

LISTING OF VARIABLES

List of Variables

Symbol	Type of equation	Definition
APCWFP	A	ACTUAL PAYMENT FOR CONSTRUCTION WORKFORCE AND PROCUREMENT (DOLLAR)
APDWF	A	ACTUAL PAYMENT FOR DESIGN WORKFORCE (DOLLAR)
APPRGC	A	APPARENT PROGRESS (CONST JOB/WEEK)
APPRGD	A	APPARENT PROGRESS IN DESIGN (DRAWING/WEEK)
APRODC	A	APPARENT PRODUCTIVITY IN CONST (CONST JOB/PERSON- WEEK)
APRØDD	A	APPARENT PRODUCTIVITY IN DESIGN (DRAWING/PERSON-WEEK)
ARC	E	ARCHITECTURE
ASIDYC	P	ASSIMILATION DELAY OF PERSON IN CONST (WEEK)
ASIDYD	P	ASSIMILITION DELAY IN DESIGN (WEEK)
ASIMRC	R	ASSIMILITION RATE OF NEW PERSON IN CONST (PERSON/WEEK)
ASIMRD	R	ASSIMILATION RATE IN DESIGN (PERSON/WEEK)
AVEMTD	P	AVERAGE EMPLOYMENT TIME (WEEK)
AVEPTC	P	AVERAGE EMPLOYMENT TIME IN CONST (WEEK)
AVQD	A	AVERAGE QUALITY OF DESIGN (DIMENSIONLESS)
CAPAY	L	CUMULATIVE ACTUAL PAYMENT (DOLLAR)
CAPRGC	A	CALIBRATED PROGRESS IN CONST (DIMENSIONLESS)
CAPRGD	A	CALIBRATED PROGRESS IN DESIGN
CCCOS	A	CUMULATIVE MANPOWER CONST COST (DOLLAR)
CCOSSF	C	CONST COST PER SQUARE FOOT (DOLLAR/SQUARE FOOT)
CCWFD	L	CUMULATIVE CONST WORKFORCE-DAYS (PERSON-DAYS)
CAD	A	COMPLETION DATE OF CONST TAKING INTO ACCOUNT OF DESIGN COMPLETION DATE (WEEK)
CDCNAD	A	COMPLETION DATE OF CONST NOT TAKING INTO ACCOUNT OF DESIGN COMPLETION DATE (WEEK)
CELDWF	A	CEILING ON DESIGN WORKFORCE (PERSON)
CEPREM	A	CONST EFFORT PERCEIVED REMAINING (PERSON-WEEK)
CHIRDY	C	CONSTRUCTION HIRING DELAY (WEEK)
CHIRER	R	CONST HIRING RATE (PERSON/WEEK)

CLTCWF	A	CEILING ON TOTAL CONST WORKFORCE (PERSON)
CNNR	L	CONST NOT NEEDING REWORKED (CONSTRUCTION JOB)
CNNRPD	L	PROGRESS NOT NEEDING REWORK TO FIND REAL PRODUCTIVITY PER DELTA TIME (CONST JOB)
CONSST	C	CONST START TIME (WEEK)
CPADCE	C	COMPLETION PERCENTAGE OF ARCHITECTURAL DESIGN COMPARED TO ELECTRICAL (DIMENSIONLESS)
CPADCM	C	COMPLETION PERCENTAGE OF ARC DESIGN COMPARED TO MEC (DIMENSIONLESS)
CPCDCA	C	COMPLETION PERCENTAGE OF CIVIL DESIGN COMPARED TO ARC (DIMENSIONLESS)
CPCP	A	CUMULATIVE PERCEIVED CONSTRUCTION PROGRESS (CONST JOB)
CPPRGD	A	CUMULATIVE PERCEIVED PROGRESS IN DESIGN (DRAWINGS)
CPPROD	A	CONST PERCEIVED PRODUCTIVITY (CONST JOB/PERSON-WEEK)
CRPROD	A	CONSTRUCTION REAL PRODUCTIVITY (CONST JOB/PERSON-WEEK)
CSAT	A	CONST SCHEDULE ADJUSTEMENT TIME (WEEK)
CTRRD	L	CONST TO REVISED DUE TO REVISED DESIGN (CONST-JOBS)
CWEQ	A	CONST WORKFORCE EXPERIENCE EFFECT ON QUALITY (DIMENSIONLESS)
CWFDD	L	CUMULATIVE WORKFORCE-DAYS IN DESIGN (PERSON-DAYS)
CWFEXP	L	CONST WORKFORCE WITH EXPERIENCE (PERSON)
CWFGAP	A	CONST WORKFORCE GAP (PERSON)
CWFND	A	CONST WORKFORCE NEEDED (PERSON)
CWFNEW	L	CONSTRUCTION WORKFORCE THAT ARE NEW (PERSON)
CWFQF	A	CONST WORKFORCE QUALITY FACTOR (DIMENSIONLESS)
CWFS	A	CONST WORKFORCE SOUGTH (PERSON)
DACCAD	C	DIFFERENCE BETWEEN ARCHITECTURE AND CIVIL TO CONTINUE THE ARCHITECTURAL DESIGN (DIMENSIONLESS)
DARSCD	A	DURATION ADDS DUE TO REVISED SCHEDULE COMPLETION DATE IN DESIGN
DC	C	DESIGN CHANGE (DRAWING)
DCOSTH	C	DESIGN COST PER HOUR (DOLLAR/HOUR)
DELDY	A	DELIVERY DELAY (WEEK)
DELRML	R	DELIVERY RATE OF MATL (PIECE/WEEK)
DELYF	C	DELIVERY FACTOR (DIMENSIONLESS)
DEMCMD	C	DIFFERENCE BETWEEN ELE & MEC TO CONTINUE THE MEC DESIGN (DIMENSIONLESS)
DEPREM	A	DESIGN EFFORT PERCEIVED REMAINING (PERSON-DAYS)
DI	F	SPECIALTIES: CIVIL, MECHANICAL,

		ELECTRICAL, ARCHITECTURAL AND INTERIOR
DI3	F	SPECIALTY: MECHANICAL
DIECED	C	DIFFERENCE BETWEEN INT & ELE TO CONTINUE THE ELE DESIGN (DIMENSIONLESS)
DIMCMD	C	DIFFERENCE BETWEEN INTERIOR AND MECHANIC TO CONTINUE THE MECHANICAL DESIGN (DIMENSIONLESS)
DNNR	L	DRAWING NOT NEEDING REWORK (CUMULATIVE REAL PROGRESS) (DRAWING)
DNNRP	L	DESIGN NOT NEEDING REWORK TO FIND THE REAL PRODUCTIVITY (DRAWING)
DPPROD	A	DESIGN PERCEIVED PRODUCTIVITY (DRAWING/PERSON-WEEK)
DQMWA	A	DESIGN QUALITY MULTIPLIER DUE TO THE RATIO OF WORK ADDED (DIMENSIONLESS)
DRDC	L	DRAWING TO REWORK DUE TO DESIGN CHANGE (DRAWING)
DRPROD	A	DESIGN REAL PRODUCTIVITY (DRAWING/PERSON-WEEK)
DRSSC	A	DELAY TO RECOGNISE SCHEDULE SITUATION IN CONST (WEEK)
DRSSD	A	DELAY TO RECOGNISE SCHEDULE SITUATION IN DESIGN (WEEK)
DSC	A	DURATION OF SPECIALTIES IN CONST (WEEK)
DSDC	A	DETERMINATION OF START DATES IN CONST (WEEK)
DSDD	A	DETERMINATION OF START DATES IN DESIGN (WEEK)
DSTC	L	DETERMINATION OF START TIMES IN CONST (WEEK)
DSTD	L	DETERMINATION OF START TIMES IN DESIGN (WEEK)
DT	S	DELTA TIME (WEEK)
DTRASC	L	DRAWINGS TO REWORK AFTER THE CONSTRUCTION START (DRAWING)
DTRDC	R	RATE OF DRAWING TO REWORK DUE TO DRAWING CHANGED (DRAWING/WEEK)
DTRWA	R	DESIGN TO REWORK DUE TO WORK ADDED IN DESIGN (DRAWING/WEEK)
DTRWAD	L	DRAWING TO REWORK DUE TO WORK ADDED IN DESIGN (DRAWING)
DURCN	C	DURATION OF DISCIPLINES IN CONST INITIALLY (WEEK)
DURDN	C	DURATION OF DISCIPLINES IN DESIGN INITIALLY (WEEK)
DWFS	A	DESIGN WORKFORCE SOUGTH (PERSON)
EFAWLC	A	EFFECT OF AREA WORKLOAD IN CONST (DIMENSIONLESS)
EFDMP	A	EFFECT OF DELIVERED MATERIAL ON APPARENT CONST.PRODUCTIVITY (DIMENSIONLESS)
EFDMQ	A	EFFECT OF DELIVERED MATERIAL ON QUALITY OF CONST (DIMENSIONLESS)

EFESCC	C	EFFECTIVE ESCALATION COST (DIMENSIONLESS)
EFESCD	C	EFFECTIVE ESCALATION COST (DIMENSIONLESS)
EFINT	C	EFFECTIVE INTEREST (DIMENSIONLESS)
EFJSC	A	EFFECT OF JOB SIZE IN CONST (DIMENSIONLESS)
EFJSD	A	EFFECT OF JOB SIZE ON DESIGN PRODUCTIVITY (DIMENSIONLESS)
EFOVTC	A	EFFECT OF OVERTIME IN CONST (DIMENSIONLESS)
ELE	E	ELECTRIC
EQDRC	A	EFFECT ON QUALITY OF DESIGN REVISED DURING THE CONST (DIMENSIONLESS)
EVLC	A	EFFECT OF VACATIONS ON LEARNING EFFECT (DIMENSIONLESS)
EWAQD	A	EFFECT OF WORK ADDED ON QUALITY IN DESIGN (DIMENSIONLESS)
EXPTRC	A	EXPERIENCED TRANSFERED PERSON IN CONST (PERSON/WEEK)
EXPTRD	A	EXPERIENCED WORKFORCE TRANSFER IN DESIGN (PERSON/WEEK)
FICWF	A	FACTOR FOR THE INDICATED WORKFORCE TAKING INTO ACCOUNT OF RELATIONS IN CONST (DIMENSIONLESS))
FIWFD	A	FACTOR FOR THE INDICATED WORKFORCE TAKING INTO ACCOUNT OF RELATIONS IN DESIGN (DIMENSIONLESS))
FLAGCS	L	FLAG IN CONST FOR START DATES (FLAG)
FLAGDS	L	FLAG IN DESIGN FOR START DATES (FLAG)
FLAGRD	R	FLAG RATE IN DESIGN TO DETERMINE START DATES IN DESIGN ("FLAG"/WEEK)
FLAREA	C	FLOOR AREA (SQUARE FEET)
FLARIC	R	FLAG RATE INDICATOR IN CONST TO FIND START DATES IN CONST (1/WEEK)
FOVTAC	A	FACTOR FOR OVERTIME HOUR IN CONST DUE TO ACCELERATION (DIMENSIONLESS)
FPASED	C	FURTHER PROGRESS OF ARC TO STUDY THE ELE DESIGN (DIMENSIONLESS)
FPASMD	C	FURTHER PROGRESS OF ARC TO STUDY THE MEC DESIGN (DIMENSIONLESS)
FPAY	A	FINANCIAL PAYMENT (DOLLAR)
FPCOMC	A	FRACTION PERCEIVED COMPLETE IN CONSTRUCTION (DIMENSIONLESS)
FPCOMD	A	FRACTION PERCEIVED COMPLETED IN DESIGN (DIMENSIONLESS)
GPRODC	C	GROSS PRODUCTIVITY IN CONST (CONSTRUCTION JOBS/PERSON-WEEK)
GPRODD	C	GROSS PRODUCTIVITY IN DESIGN (DRAWING/PERSON-WEEK)
HIRDYD	P	HIRING DELAY IN DESIGN (WEEK)
HIRERD	R	HIRING RATE DESIGN (PERSON/WEEK)

ICDC	A	INDICATED COMPLETION DATE IN CONSTRUCTION (WEEK)
ICDD	A	INDICATED COMPLETION DATE IN DESIGN (WEEK)
ICWFTR	A	INDICATED CONST WORKFORCE TAKING INTO ACCOUNT OF RELATIONS (PERSON)
ICWFWR	A	INDICATED CONST WORKFORCE WITHOUT TAKING INTO ACCOUNT OF RELATIONS (PERSON)
INT	E	INTERIOR
IPRODC	A	INDICATED PRODUCTIVITY IN CONST (CONST JOB/PERSON-WEEK)
IPRODD	A	INDICATED PRODUCTIVITY IN DESIGN (DRAWING/PERSON-WEEK)
IW	C	INITIAL WORK IN DESIGN (DRAWING)
IWFD	A	INDICATED WORKFORCE IN DESIGN (PERSON)
IWFDWR	A	INDICATED WORKFORCE IN DESIGN TAKING INTO ACCOUNT OF RELATIONS (PERSON)
LENGTH	S	LENGTH OF THE SIMULATION (WEEK)
LEPROC	A	LEARNING EFFECT IN CONST (DIMENSIONLESS)
LEPROD	A	LEARNING EFFECT ON PRODUCTIVITY IN DESIGN (DIMENSIONLESS)
LTBSC	A	LATEST TIME BETWEEN THESE SPECIALTIES (WEEK)
MAXRQM	C	MAXIMUM REQUISITIONS RATE OF MATL (PIECE/WEEK)
MEC	E	MECHANICAL
MHCOSC	C	MAN-HOUR COST IN CONSTRUCTION (DOLLAR/HOUR)
MTLND	A	MATERIAL NEEDED (IN THEORY) (DIMENSIONLESS)
MTLODR	L	MATERIAL ORDERS (DIMENSIONLESS)
MTLOST	L	MATERIAL ON SITE (PIECE)
NACS	R	NET ADDITION TO CONST SCHEDULE (WEEK/WEEK)
NASD	R	NET ADDITION TO SCHEDULE IN DESIGN (WEEK/WEEK)
NBERDW	C	NUMBER OF DAYS PER WEEK (WORKING DAYS/WEEK)
NBRFLR	A	NUMBER OF FLOORS (FLOOR)
NBRHDC	C	NUMBER OF HOURS PER DAY IN CONST (WORKING HOURS/DAY)
NBRHDD	C	NUMBER OF HOUR PER DAY IN DESIGN (HOURS/DAY)
NESCFC	A	NOMINAL ESCALATION FACTOR FOR CONSTRUCTION (DIMENSIONLESS)
NESCFD	A	NOMINAL ESCALATION FACTOR FOR DESIGN (DIMENSIONLESS)
NEWCTR	A	NEW CONST TRANSFER RATE (PERSON/WEEK)
NEWTRD	A	NEW TRANSFER RATE IN DESIGN (PERSON/WEEK)
NHOTCA	C	NUMBER OF HOURS ON OVERTIME DUE TO ACCELERATION IN CONST (HOUR)

NHWC	A	NUMBER OF HOURS PER WEEK IN CONST (HOUR)
NINTRF	A	NOMINAL INTEREST FACTOR (DIMENSIONLESS)
NWAR	A	NOTICE OF WORK ADDED RATE TO AFFECT THE DESIGN QUALITY (DRAWINGS/WEEK)
ODRMTL	R	ORDERS RATE OF MATERIAL (% PIECE/WEEK)
ORDY	P	ORDERS DELAY (WEEK)
OVRTHC	A	OVERTIME HOURS IN CONST (HOUR)
PACED	C	PROGRESS OF ARC TO CONTINUE THE ELE DESIGN (DIMENSIONLESS)
PADBCD	C	PROGRESS OF ARC DESIGN BEFORE CIV DESIGN START (DIMENSIONLESS)
PADBID	C	PROGRESS OF ARC DESIGN BEFORE INT DESIGN START (DIMENSIONLESS)
PADBMD	C	PROGRESS OF ARC DESIGN BEFORE CIV DESIGN START (DIMENSIONLESS)
PASPCD	C	PROGRESS OF ARC TO STUDY THE PROGRESS OF CIV DESIGN (DIMENSIONLESS)
PCCAD	C	PROGRESS OF CIV TO COMPLETE THE ARC DESIGN (DIMENSIONLESS)
PCSED	C	PROGRESS OF CIV TO STUDY THE ELE DESIGN (DIMENSIONLESS)
PCSMD	C	PROGRESS OF CIV TO STUDY THE MEC DESIGN (DIMENSIONLESS)
PECAD	C	PROGRESS OF ELE TO COMPLETE THE ARC DESIGN (DIMENSIONLESS)
PECCD	C	PROGRESS OF ELE TO CONTINUE THE CIV DESIGN (DIMENSIONLESS)
PEDBID	C	PROGRESS OF ELE DESIGN BEFORE INT DESIGN START (DIMENSIONLESS)
PESIED	C	PROGRESS OF ELE TO STUDY THE INT & ELE DESIGN (DIMENSIONLESS)
PESPAD	C	PROGRESS OF ELE TO STUDY THE PROGRESS OF ARC AND MEC DESIGN (DIMENSIONLESS)
PMCCD	C	PROGRESS OF MEC TO CONTINUE THE CIV DESIGN (DIMENSIONLESS)
PMDBID	C	PROGRESS OF MEC DESIGN BEFORE INT DESIGN START (DIMENSIONLESS)
PMSID	C	PROGRESS OF MEC TO STUDY THE INT DESIGN (DIMENSIONLESS)
PMSPE	C	PROGRESS OF MEC TO STUDY THE PROGRESS WITH ELE DESIGN (DIMENSIONLESS)
POMTL	A	POTENTIAL ORDERS RATE OF MATERIAL IN RELATION WITH DESIGN PROGRESS (% PIECE/WEEK)
PPABCD	C	PERCENTAGE OF PROGRESS OF ARC BEFORE CIV DESIGN (DIMENSIONLESS)
PPABED	C	PERCENTAGE OF PROGRESS OF ARC BEFORE ELE DESIGN (DIMENSIONLESS)
PPABID	C	PERCENTAGE OF PROGRESS OF ARC BEFORE INT DESIGN (DIMENSIONLESS)
PPABMD	C	PERCENTAGE OF PROGRESS OF ARC BEFORE MEC

		DESIGN (DIMENSIONLESS)
PPCBAW	C	PERCENTAGE PROGRESS OF CIV BEFORE ARC WORK START (DIMENSIONLESS)
PPCBEW	C	PERCENTAGE PROGRESS OF CIV BEFORE ELE WORK START (DIMENSIONLESS)
PPCBMW	C	PERCENTAGE PROGRESS OF CIV BEFORE MEC WORK START (DIMENSIONLESS)
PPEBIW	C	PERCENTAGE PROGRESS OF ELE BEFORE INT WORK START (DIMENSIONLESS)
PRGRC	A	PROGRESS RATIO IN CONST (DIMENSIONLESS)
PRGRD	A	PROGRESS RATIO IN DESIGN (DIMENSIONLESS)
PROCF	C	PROCUREMENT COST FACTOR (DIMENSIONLESS)
PROCST	C	PROCUREMENT START TIME (WEEK)
PSDLEC	C	PROGRESS OF CONST BEFORE STARTING TO DECREASE THE LEARNING FACTOR (DIMENSIONLESS)
PSDLED	C	PROGRESS OF DESIGN BEFORE STARTING TO DECREASE THE LEARNING FACTOR IN DESIGN (DIMENSIONLESS)
PW	L	PRESENT WORTH OF PAYMENT
PWANAD	A	PERCENTAGE OF WORK ADDED NOT AFFECTING THE DESIGN (DIMENSIONLESS)
QC	A	QUALITY OF CONSTRUCTION (DIMENSIONLESS)
QD	A	QUALITY OF DESIGN (DIMENSIONLESS)
QDEL	P	QUALITY DELAY (WORKING WEEKS)
QDGN	A	QUALITY OF DESIGN TO DETERMINE THE QUALITY OF SHOP DRAWINGS (DIMENSIONLESS)
QDSD	A	QUALITY OF DESIGN OF SHOP DRAWINGS (DIMENSIONLESS)
QUITRC	R	QUIT RATE IN CONST (PERSON/WEEK)
QUITRD	R	QUIT RATE IN DESIGN (PERSON/WEEK)
RATCWF	A	RATIO OF AREA TO TOTAL CONST WORKFORCE (SQUARE FOOT/PERSON)
RCD	C	RATIO CONSTRUCTION TO DESIGN MAN-HOUR (DIMENSIONLESS)
RCNNR	R	RATE OF CONSTRUCTION NOT NEEDING REWORK (CONSTRUCTION JOBS/WEEK)
RCPPPC	A	RATIO OF CALIBRATED PROGRESS TO PERCEIVED PROGRESS IN CONST (DIMENSIONLESS)
RCPPPD	A	RATIO OF CALIBRATED PROGRESS TO PERCEIVED PROGRESS IN DESIGN (DIMENSIONLESS)
RCTRRD	R	RATE OF CONST TO REWORK DUE TO REVISED DESIGN (CONST JOB/WEEK)
RDNNR	R	RATE OF DRAWING NOT NEEDIND REWORK (DRAWING/WEEK)
RDNNR2	R	RATE OF DRAWING NOT NEEDING REWORK #2 (AT TIME.K-DT) TO FIND THE REAL PRODUCTIVITY (DRAWING/WEEK)
RDRASC	A	RATE OF DRAWING TO REWORK AFTER THE

		START OF THE CONST(DRAWING/WEEK)
RDTTPC	C	RATIO OF DESIGN COST TO TOTAL PROJECT COST (DIMENSIONLESS)
RDUCNR	R	RATE OF DETECTION OF UNDISCOVERD CONST JOB NEEDING REWORK (CONSTRUCTION JOBS/WEEK)
RDUDNR	R	RATE OF DETECTION OF UNDISCOVERED DESIGN NEEDING REWORK (DRAW/WEEK)
REQDY	P	REQUISITION DELAY (WEEK)
REQMTL	L	REQUISITIONS OF MATERIAL (PIECE)
REQRML	R	REQUISITIONS RATE OF MATERIAL (PIECE/WEEK)
RFCOMC	A	REAL FRACTION COMPLETE IN CONST (DIMENSIONLESS)
RFCOMD	A	REAL FRACTION COMPLETE IN DESIGN (DIMENSIONLESS)
RICWFO	A	RATIO FOR THE INDICATED CONSTRUCTION WORKFORCE FOR OVERTIME (DIMENSIONLESS)
RLOPPC	A	REDUCTION OF LEARNING OVER A PERCEIVED PROGRESS OF DESIGN (DIMENSIONLESS)
RLOPPD	A	REDUCTION OF LEARNING OVER A PERCEIVED PROGRESS OF DESIGN (DIMENSIONLESS)
RMPTCC	C	RATIO MANPOWER COST TO TOTAL CONSTRUCTION COST (DIMENSIONLESS)
RMSMN	A	RATIO OF MATL ON SITE TO MATL NEEDED (DIMENSIONLESS)
RONHWC	A	RATIO OVERTIME TO NORMAL NUMBER OF HOURS PER WEEK IN CONST (DIMENSIONLESS)
RRDCTD	A	RATIO OF REVISED DRAW DURING THE CONST TO TOTAL DRAW (DIMENSIONLESS)
RTRAFC	A	REQUIRED TRAPEZOIDAL FACTOR IN CONST (DIMENSIONLESS)
RTRAFD	A	REQUIRED TRAPEZOIDAL FACTOR IN DESIGN (DIMENSIONLESS)
RUCNR	R	RATE OF UNDISCOVERED CONST JOBS NEEDING REWORK (CONST JOB/WEEK)
RUDNR	R	RATE OF UNDISCOVERED DESIGN NEEDING REWORK (DRAWING/WEEK)
RWATW	A	RATIO OF WORK ADDED TO TOTAL WORK IN DESIGN (DIMENSIONLESS)
SATD	A	SCHEDULE ADJUSTEMENT TIME IN DESIGN (WEEK)
SAVPER	S	SAVE PERIOD (WEEK)
SCDC	L	SCHEDULE COMPLETION DATE IN CONSTRUCTION (WEEK)
SCDCN	A	SCHEDULE COMPLETION DATE IN CONSTRUCTION INITIALLY (WEEK)
SCDD	L	SCHEDULE COMPLETION DATE IN DESIGN (WEEK)
SCDND	A	SCHEDULE COMPLETION DATE INITIALLY IN DESIGN (WEEK)
SCPEPC	A	SCHEDULE PRESSURE EFFECT ON PRODUCTIVITY

		IN CONST (DIMENSIONLESS)
SCPEPD	A	SCHEDULE PRESSURE EFFECT ON PRODUCTIVITY IN DESIGN (DIMENSIONLESS)
SCPEQC	A	SCHEDULE PRESSURE EFFECT ON QUALITY IN CONST (DIMENSIONLESS)
SCPEQD	A	SCHEDULE PRESSURE EFFECT ON QUALITY IN DESIGN (DIMENSIONLESS)
SQD	L	SUMMATION OF QUALITY DESIGN (DIMENSIONLESS)
T2	C	TIME TO START THE WORK ADDED (WEEK)
T3	C	INTERVAL TIME TO ADD WORK (WEEK)
T4	C	TIME TO START THE DESIGN CHANGED (WEEK)
T5	C	INTERVAL TIME TO DESIGN CHANGED (WEEKS)
TAPAY	A	TOTAL ACTUAL PAYMENT (DOLLARS)
TCAPRC	T	TABLE FOR CALIBRATED PROGRESS IN CONST (DIMENSIONLESS)
TCAPRD	T	TABLE FOR CALIBRATION PROGRESS ON DESIGN (DIMENSIONLESS)
TCDWF	T	TABLE FOR CEILING ON DESIGN WORKFORCE (PERSON)
TCONSC	A	TOTAL MANPOWER CONSTRUCTION COST (DOLLAR)
TCOSTC	A	TOTAL COST TAKING INTO ACCOUNT THE CONST COST (DOLLAR)
TCOSTD	A	TOTAL COST TAKING INTO ACCOUNT OF DESIGN COST (DOLLAR)
TCTCWF	T	TABLE FOR CEILING ON TOTAL CONST WORKFORCE (PERSON)
TCWF	A	TOTAL CONSTRUCTION WORKFORCE IN EACH SPECIALTY (PERSON)
TCWFAS	A	TOTAL CONST WORKFORCE WITH ALL THE SPECIALTIES (PERSON)
TDCR	P	TIME TO DETECT CONST TO REWORK (WEEK)
TDCRW	A	TIME TO DETECT CONST REWORK (WEEK)
TDDR	P	TIME TO DETECT REWORK (ON GOOD DESIGN) (WEEK)
TDELDY	T	TABLE FOR DELIVERY DELAY (WEEK)
TDESC	A	TOTAL DESIGN COST (DOLLAR)
TDQMWA	T	TABLE FOR DESIGN QUALITY MULTIPLIER DUE TO WORK ADDED (DIMENSIONLESS)
TDRSS	T	TABLE FOR DELAY TO RECOGNIZE SCHEDULE SITUATION IN DESIGN (WEEK)
TDRW	A	TIME TO DETECT REWORK (WEEK)
TDWF	A	TOTAL DESIGN WORKFORCE IN EACH SPECIALTY (PERSON)
TDWFAS	A	TOTAL DESIGN WORKFORCE WITH ALL THE SPECIALTIES (PERSON)
TEFAWL	T	TABLE FOR THE EFFECT OF AREA WORKLOAD IN CONST (DIMENSIONLESS)
TEFDMP	T	TABLE FOR THE EFFECT OF DELIVERED MATL ON PRODUCTIVITY (DIMENSIONLESS)
TEFDMQ	T	TABLE FOR THE EFFECT OF DELIVERED MATL

		ON QUALITY OF CONST (DIMENSIONLESS)
TEFJSC	T	TABLE FOR THE EFFECT OF JOB SIZE IN CONST (DIMENSIONLESS)
TEFJSD	T	TABLE FOR THE EFFECT OF JOB SIZE IN DESIGN (DIMENSIONLESS)
TEFOVT	T	TABLE FOR THE EFFECT OF OVERTIME IN CONST (DIMENSIONLESS)
TEWAQD	T	TABLE OF EFFECT OF WORK ADDED ON QUALITY IN DESIGN (DIMENSIONLESS)
TLEPC	T	TABLE FOR THE LEARNING EFFECT ON PRODUCTIVITY IN CONST (DIMENSIONLESS)
TLEPD	T	TABLE FOR LEARNING EFFECT ON PRODUCTIVITY (DIMENSIONLESS)
TOVTC	T	TABLE FOR OVERTIME IN CONSTRUCTION (HOUR)
TPCJ	A	TOTAL PERCEIVED CONSTRUCTION JOBS (CONSTRUCTION JOBS)
TPCMD	A	TOTAL PERCEIVED CONST MAN-DAYS IN EACH SPECIALTY (PERSON-DAYS)
TPCOST	A	TOTAL AVERAGE PROJECT COST (CONSTANT DOLLAR)
TPDMD	A	TOTAL PERCEIVED DESIGN MAN-DAYS (PERSON-DAYS)
TPOMTL	T	TABLE FOR THE POTENTIAL ORDERS RATE OF MATERIAL IN RELATION WITH DESIGN PROGRESS (DIMENSIONLESS)
TPPROD	P	TIME TO PERCEIVED PRODUCTIVITY IN DESIGN (WORKING WEEK)
TPREQC	A	TIME PERCEIVED REQUIRED IN CONST (WEEK)
TPREQD	A	TIME PERCEIVED REQUIRED IN DESIGN (WEEK)
TPRGRC	A	TIME PROGRESS IN CONST (DIMENSIONLESS)
TPWANA	T	TABLE FOR THE PERCENTAGE OF WORK ADDED NOT AFFECTING THE DESIGN (DIMENSIONLESS)
TQC	T	TABLE FOR QUALITY OF CONSTRUCTION (DIMENSIONLESS)
TQD	T	TABLE FOR QUALITY OF DESIGN (DIMENSIONLESS)
TQDSD	T	TABLE FOR THE QUALITY OF DESIGN OF SHOP DRAWINGS (DIMENSIONLESS)
TQMRDC	T	TABLE FOR QUALITY MOTIVATION OF WORKERS DUE TO REVISED DESIGN IN CONST (DIMENSIONLESS)
TREMC	A	TIME REMAINING IN CONSTRUCTION (WEEK)
TREMD	A	TIME REMAINING IN DESIGN (WORKING WEEK)
TRNFRC	A	TRANSFER RATE OF PERSON IN CONST (PERSON/WEEK)
TRNFRD	A	TRANSFER RATE IN DESIGN (PERSON/WEEK)
TRNSDY	P	TRANSFER DELAY (WEEK)
TRTRFC	T	TABLE FOR REQUIRED TRAPEZOIDAL FACTOR IN CONST (DIMENSIONLESS)

TRTRFD	T	TABLE FOR THE REQUIRED TRAPEZOIDAL FACTOR IN DESIGN (DIMENSIONLESS)
TSATC	T	TABLE FOR SCHEDULE ADJUSTMENT TIME IN CONST (WEEK)
TSATD	T	TABLE FOR SCHEDULE ADJUSTMENT TIME IN DESIGN (WEEK)
TSCPEQ	T	TABLE FOR SCHEDULE PRESSURE ON QUALITY (DIMENSIONLESS)
TSPEP	T	TABLE FOR THE SCHEDULE PRESSURE EFFECT ON PRODUCTIVITY (DIMENSIONLESS)
TTDRW	T	TABLE FOR TIME TO DETECT REWORK (WEEK)
TWA	A	TOTAL WORK ADDED (DRAWING)
TWCCWF	T	TABLE FOR THE WILLINGNESS TO CHANGE CONST WORKFORCE (DIMENSIONLESS)
TWCWFD	T	TABLE FOR THE WILLINGNESS TO CHANGE WORKFORCE IN DESIGN (DIMENSIONLESS)
TWRSPC	T	TABLE FOR THE WILLINGNESS TO RECOGNIZE PRESSURE DUE TO PROGRESS IN CONST (DIMENSIONLESS)
TWRSPD	T	TABLE FOR THE WILLINGNESS TO RECOGNIZE THE PRESSURE DUE TO THE PROGRESS IN DESIGN (DIMENSIONLESS)
TWEQ	T	TABLE FOR WORFORCE EXPERIENCE EFFECT ON QUALITY (DIMENSIONLESS)
TWTRP	T	TABLE FOR WILLINGNESS TO TAKE THE REAL PRODUCTIVITY (DIMENSIONLESS)
UCNR	L	UNDISCOVERED CONST JOBS NEEDING REWORK (CONSTRUCTION JOBS)
UDR	L	UNDISCOVERED DRAWINGS TO REWORK (DRAWING)
UDNR	L	UNDISCOVERED DESIGN NEEDING REWORK (DRAWING)
V1	C	FACTOR FOR THE EFFECT OF VACATIONS ON LEARNING (DIMENSIONLESS)
V2	A	FIRST TIME FOR THE EFFECT OF HOLYDAYS ON LEARNING (WEEK)
V3	C	REPEATED TIME FOR THE EFFECT OF HOLYDAYS ON LEARNING (WEEK)
WA	C	WORK ADDED (DRAWING)
WAAPD	L	WORK ADDED AFFECTING PROGRESS IN DESIGN (DRAWING)
WANAPD	L	WORK ADDED NOT AFFECTING PROGRESS IN DESIGN (DRAWING)
WARAD	R	WORK ADDED RATE AFFECTING THE DESIGN (DRAWING/WEEK)
WARNAD	R	WORK ADDED RATE NOT AFFECTING THE DESIGN (DRAWING/WEEK)
WCCWF	A	WILLINGNESS TO CHANGE CONST WORKFORCE (DIMENSIONLESS)
WCEDAI	C	WEEKS COMPLETED OF ELECTRICAL DESIGN AFTER INT DESIGN (WEEK)
WCMDAI	C	WEEKS COMPLETED OF MECHANICAL DESIGN

		AFTER INT DESIGN (WEEK)
WCWFD	A	WILLINGNESS TO CHANGE WORKFORCE IN DESIGN (DIMENSIONLESS)
WEDBCI	C	WEEKS OF ELECTRICAL DESIGN BEFORE COMPLETION OF INT DESIGN
WEQD	A	WORKFORCE EXPERIENCE ON QUALITY IN DESIGN (DIMENSIONLESS)
WFDYD	C	WORKFORCE DELAY IN DESIGN TO TRANSFER PERSON DUE TO RELATIONS (WEEK)
WFEXPD	L	WORKFORCE WITH EXPERIENCE IN DESIGN (PERSON) WORKFORCE WITH EXPERIENCE IN DESIGN FOR ARCHITECTURAL WORK (PERSON)
WFGAPD	A	WORKFORCE GAP IN DESIGN (PERSON)
WFNEED	A	WORKFORCE NEEDED IN DESIGN (PERSON)
WFNEWD	L	WORKFORCE NEW IN DESIGN (PERSON)
WFQFD	A	WORKFORCE QUALITY FACTOR IN DESIGN (DIMENSIONLESS)
WMDBCI	C	WEEKS OF MECHANICAL DESIGN BEFORE COMPLETION OF INT DESIGN
WOVRTA	B	WILLINGNESS TO WORK ON OVERTIME DUE TO ACCELERATION IN CONST (DIMENSIONLESS)
WOVSPC	B	WILLINGNESS FOR OVERTIME DUE TO SCHEDULE PRESSURE IN CONST (DIMENSIONLESS)
WRSPC	A	WILLINGNESS TO RECOGNIZE PRESSURE TO PROGRESS IN CONST (DIMENSIONLESS)
WRSPD	A	WILLINGNESS TO RECOGNIZE PRESSURE TO PROGRESS IN DESIGN (DIMENSIONLESS)
WTDBCE	B	SELECTION OF DESIGN COMPLETION DATE BEFORE CONST START (DIMENSIONLESS)
WTRPC	A	WILLINGNESS TO REAL PRODUCTIVITY IN CONST (DIMENSIONLESS)
WTRPD	A	WILLINGNESS TO TAKE ACCOUNT OF THE REAL PRODUCTIVITY (DIMENSIONLESS)

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LIST OF ABBREVIATIONS

arc,	architecture (exterior work)
civ,	civil
const,	construction
draw,	drawing
ele,	electric
int,	interior (architecture and finishing)
mec,	mechanic
proc,	procurement
prod,	productivity